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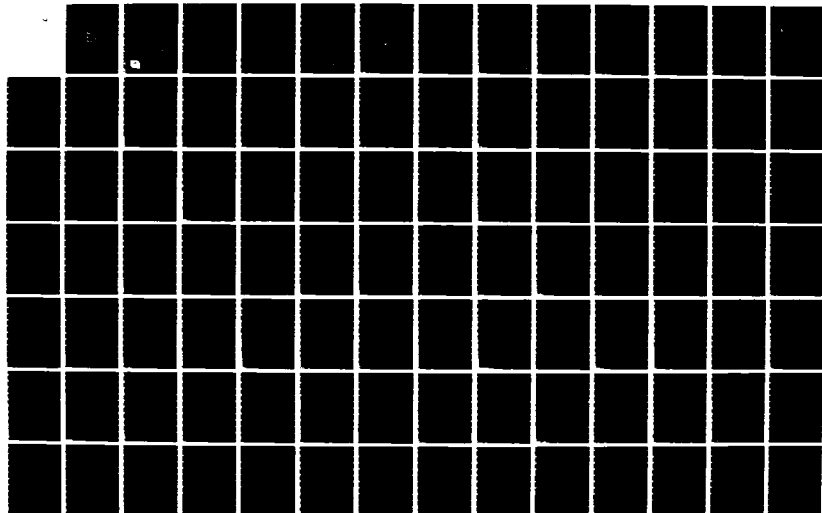
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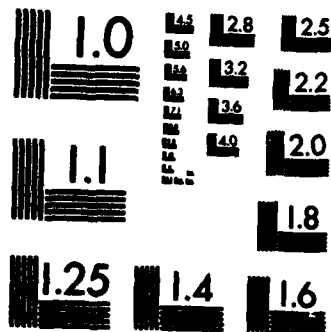
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IDA REPORT R-272

# IDA/OSD RELIABILITY AND MAINTAINABILITY STUDY

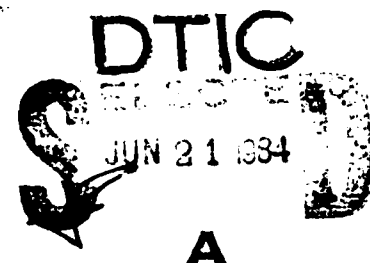
## Volume III: Case Study Analysis

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November 1983



*Prepared for*  
Office of the Under Secretary of Defense for Research and Engineering  
*and*  
Office of the Assistant Secretary of Defense  
(Manpower, Reserve Affairs and Logistics)



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**IDA/OSD RELIABILITY AND  
MAINTAINABILITY STUDY**

**Volume III: Case Study Analysis**

John R. Rivoire  
*IDA R&M Study Director*

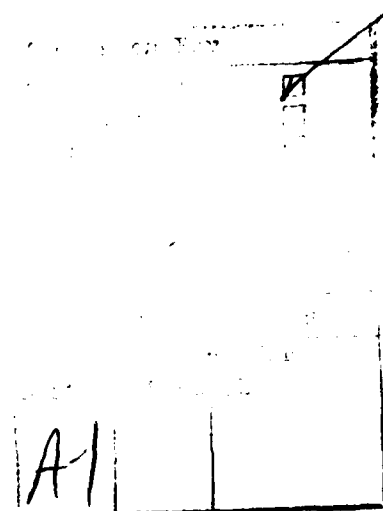
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John R. Rivoire  
Director

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## ABBREVIATIONS

A <sup>3</sup>	Affordable Acquisition Approach (USAF)
AAH	Advanced Attack Helicopter
AD	Advanced Development
AFIT	Air Force Institute of Technology
AFLC	Air Force Logistics Command
AGE	Aerospace Ground Equipment
AIS	Avionics Intermediate Shop
ALC	Air Logistics Center
ALCM	Air-Launched Cruise Missile
ALMC	Army Logistics Management Center
AMT	Accelerated Mission Testing
ASMET	Accelerated Simulated Mission Endurance Test
ATE	Advanced Technology Engine
AVIM	Aviation Intermediate Maintenance
AVUM	Aviation Unit Maintenance
AWACS	Airborne Warning and Control System
BCS	Bench-Checked Serviceable
BED	Basic Engine Development
BIS	Bureau of Inspection and Survey (Navy)
BIT	Built-In-Test
BITE	Built-In-Test Equipment
CDR	Critical Design Review
CIP	Component Improvement Program
CLEAR	Closed-Loop Evaluation and Reporting System
CND	Cannot Duplicate
CRIM	Comprehensive Record for Intensive Management
DARCOM	U.S. Army Materiel Development and Readiness Command
DESC	Defense Electronics Supply Center
DLA	Defense Logistics Agency
DMMH	Depot Maintenance Man Hours
DMMH/FH	Direct Maintenance Man Hours/Flying Hour
DPR	Development Problems Reports
DSMC	Defense Systems Management College
DT&E	Development, Test and Evaluation
ECP	Engineering Change Proposal
ED	Engineering Development
EFTC	Equivalent Full Thermal Cycle
ELCF	Equivalent Low-Cycle Fatigue
ENSIP	Engine Structural Integrity Program
EPG	European Participating Governments
ESS	Environmental Stress Screening
ETAMP	Equivalent Time at Maximum Power

FAT	Factory Acceptance Test
FD	Fault Detection
FI	Fault Isolation
FIT	Fault Isolation Test
FMC	Fully Mission Capable
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FOD	Foreign Object Damage
FOT&E	Follow-On Test and Evaluation
FRACAS	Failure Reporting, and Corrective Action System
FRB	Failure Review Board
FSD	Full-Scale Development
GCT	Government Competitive Testing
GD	General Dynamics
GFE	Government Furnished Equipment
GTV	Ground Test Vehicle
GTWT	Gridded Travelling Wave Tube
IAD	Initial Anniversary Data
IC	Integrated Circuit
ICNIA	Integrated Communications/Navigation/Identification Architecture
IDA	Institute for Defense Analyses
ILS	Integrated Logistics Support
IOT&E	Initial Operational Test and Evaluation
IPS	Inlet Particle Separator
IR&D	Independent Research and Development
JVX	Joint Services Advanced Vertical-Lift Aircraft
LCC	Life-Cycle Cost
LCF	Low-Cycle Fatigue
LDNS	Lightweight Doppler Navigation System
LMI	Logistics Management Institute
LRIP	Low Rate Initial Production
LRU	Line Replaceable Unit
MCAIR	McDonnell-Douglas Aircraft Company
MDCS	Maintenance Data Collection System
MDT	Mean Down Time
MFHBF	Mean-Flight-Hours-Between-Failure
MFHBMA	Mean-Flight-Hours-Between-Maintenance-Actions
MM	Man Month
MMH/FH	Maintenance-Man-Hours/Flight-Hour
MPGS	Mobile Protected Gun System
MQT	Mission Qualification Test
MTBF	Mean-Time-Between-Failure
MTBFRO	Mean Time Between Failure-Require Overhaul
MTBMA	Mean-Time-Between-Maintenance-Actions
MTBUMA	Mean-Time-Between-Unscheduled-Maintenance-Action

MTTR	Mean-Time-to-Repair
O&S	Operating and Support
OME	Operational Mission Environment
OMR	Operation and Maintenance Reports
OT&E	Operational Test and Evaluation
PCB	Parts Control Board
PCE	Professional Continuing Education
PDR	Preliminary Design Review
PIDS	Prime Item Development Specification
PIND	Particle Impact Noise Detection
PPSL	Program Parts Selection List
PRDR	Pre-Production Reliability Design Review
PRT	Preliminary Review Team
PRT	Production Reliability Test
R&M	Reliability and Maintainability
RADC	Rome Air Development Center
RAT	Reliability Acceptance Test
RDT	Reliability Development Test
REA	Responsible Engineering Activity
RFP	Request for Proposal
RFQ	Request for Quotation
RGT	Reliability Growth Test
RIP	Reliability Improvement Program
RIW	Reliability Improvement Warranty
RMS	Root Mean Square
ROI	Return on Investment
RQT	Reliability Qualification Test
RTOK	Retest OK
SDC	Sample Data Collection
SPO	System Program Office
SRA	Shop Replaceable Assembly
SUBACS	Submarine Advanced Combat System
SVR	Shop Visit Rate
TAAF	Test, Analyze and Fix
TBO	Time Between Overhaul
TWT	Travelling Wave Tube
UR	Unnecessary Removal
UR	Unsatisfactory Report
USAMETA	U.S. Army Management Engineering Training Agency
UTTAS	Utility Tactical Transport Aircraft System
WBS	Work Breakdown Structure
WPAFB	Wright-Patterson Air Force Base
WRA	Weapon Replaceable Assembly
WRU	Weapon Replaceable Unit



## I. INTRODUCTION

This report is a synthesis of existing case study reports, eight new case studies conducted specifically to document quantitative and qualitative data for cross-program analysis, and documents, presentations, and other available literature. It represents a portion of a large study focused on readiness through R&M. It was made possible only by the extraordinary support of the leadership and personnel of the Office of the Secretary of Defense, the military services, government, industry and academia.

The overall IDA study is divided into two major segments--one to undertake case studies of existing systems, contained in this volume, and Volume IV which examines existing opportunities to use new technology. This volume integrates the extensive case study efforts of a large-scale analysis activity, provides significant observations and findings and identifies high-payoff areas for improving weapon system readiness through innovative program structuring. The relationship of this report to the other study reports is indicated in Fig. 1.

The study was done for OASD (MRA&L) and OUSD (R&E). Russell R. Shorey (MRA&L) has been the Department of Defense point of contact throughout.

Conclusions, observations and findings from the case study analysis are contained in Section IV of this report. More detailed information is provided in the appendixes and individual case study reports.

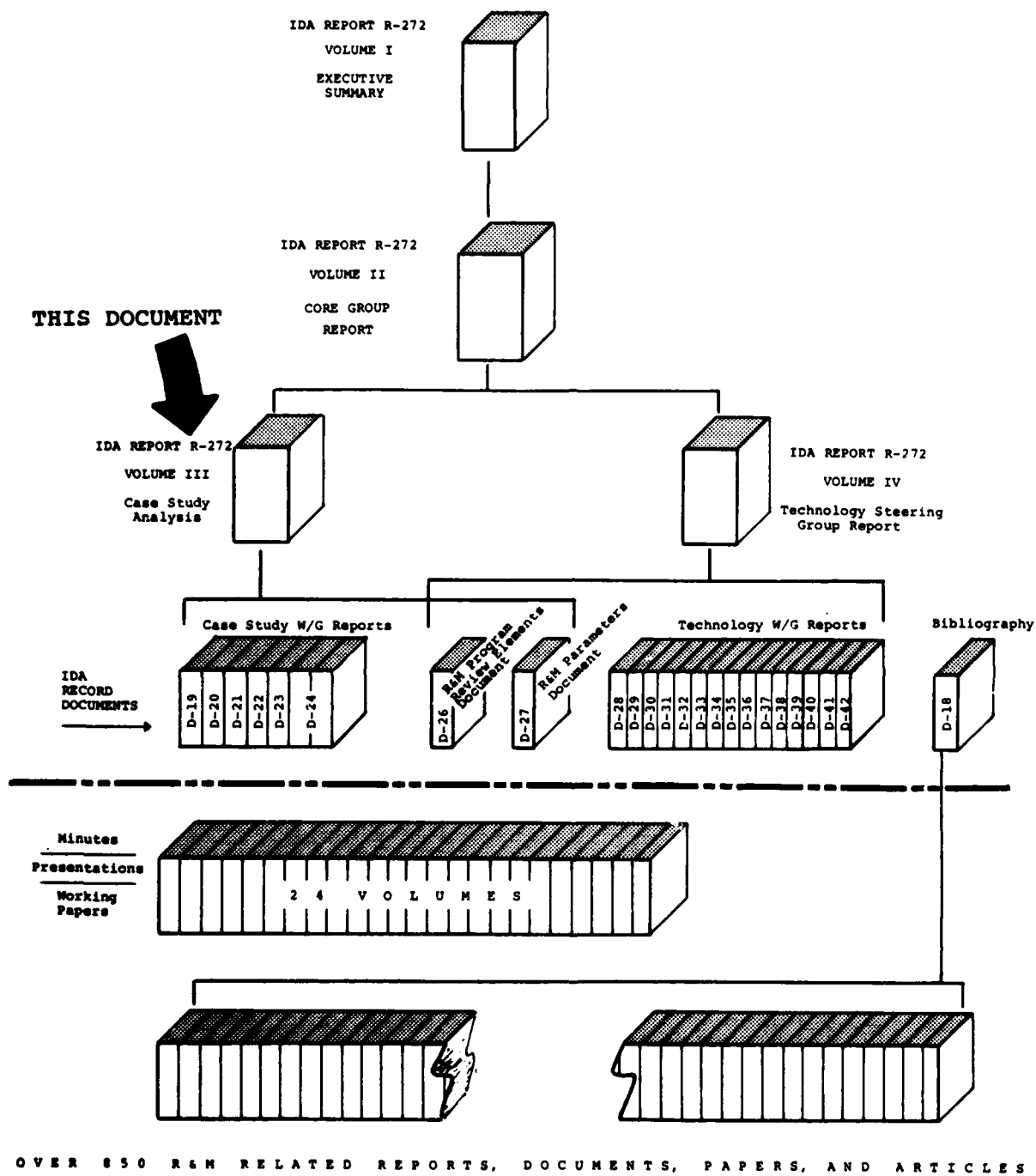


FIGURE 1. R&M Study Report Structure

## II. BACKGROUND

In recent years there has been a rising concern about DoD's ability to keep weapon systems both modern and combat-ready. At any given time the availability of many of these systems has been below that needed to maintain the required force posture. The seriousness of this problem was highlighted in the report of the 1981 Defense Science Board (DSB) study of the Operational Readiness of High Performance Systems. One of the major recommendations of that study was to design reliability into the systems from the start and mature that capability prior to full-rate production. The 1981 DSB study also highlighted problems with diagnostics and recognized that increasing system complexity, while not incompatible with readiness, made it imperative that the Department of Defense (DoD) demand and manage acquisition to achieve readiness requirements.

Because of the well publicized problems in reliability, readiness and support, DoD put improvements in this area high on its priority list. The Carlucci initiatives directed at reforming the acquisition process gave reliability and support considerations a very high priority. As a result there has been a major increase in DSARC and top management attention. On each major program there is visibility at the top on progress in meeting R&M objectives through development, production and in early field experience.

The track record from these efforts is uneven. Many of the more mature technologies have done relatively well in meeting reliability objectives. Newer, fast developing technologies often have serious problems, however, as do programs with accelerated or compressed schedules. The latter are becoming more frequent due to the Administration objectives of fielding new hardware faster. Thus, there is a major challenge in learning to manage acquisitions on accelerated programs so as

to attain desirable R&M objectives. Technology advances are potentially helpful in such areas (e.g., in electronics) by providing opportunities to improve both performance and R&M, provided the problem is attacked in both the technology base and the acquisition process.

In the future, increasing weapon system complexity and rising maintenance costs will lead to demands for higher levels of R&M. A review of the Services' Year 2000 studies identified a common theme calling for more flexibility, more autonomy, more dispersal, and reduced support tail dependency in combat forces. While the validity of the presumptions on which these requirements are based may be challenged, their general thrust is unmistakable.

As a result of these concerns, the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs and Logistics) and the Office of the Under Secretary of Defense for Research and Engineering initiated this study, "Steps Toward Improving the Materiel Readiness Posture of the DoD" (short title: R&M Study) at the Institute for Defense Analyses (IDA) with the purpose of identifying and providing support for high-payoff actions which the DoD can take to improve system design, development and support processes so as to provide quantum improvements in R&M and readiness through innovative uses of advancing technology and program structure (Appendix A, Task Order).

### III. OBJECTIVE AND SCOPE

The case study portion of the overall study addressed two distinct tasks:

- (1). To assess the impact of program structuring on future DoD requirements for improved R&M readiness; and
- (2). To evaluate the potential and recommend strategies that might result in quantum increases in R&M readiness through innovative use of program structuring.

Eight specific programs were selected for study as follows:

<u>Program</u>	<u>IDA Document No.*</u>
APG-63 Radar	D-19
APG-65 Radar	D-20
APG-66 Radar	D-21
T700 Engine	D-22
ASN-128 Radar	D-23
TPQ-36 Radar	D-24
TPQ-37 Radar	D-24
SPY-1-A Radar	

In addition, many other programs and associated reports were reviewed for specific information.

---

\*See Appendix A Reference List

To provide a framework against which other programs can be compared in terms of applicability of observations, conclusions, and findings the following points are provided,

- (1) Case Study Development Programs. The systems examined by the case studies were second and third generation radars and/or engines as opposed to a first generation system like electrooptical. The government and contractors all had experienced personnel and relatively good data bases to draw on for the then current generation of equipment.
- (2) Concurrency. Varying degrees of concurrency (overlap between development and production program phases) were examined. Observed ranges went from little concurrency on the T700 engine program to a high degree of concurrency on the APG-63 and APG-66 programs.
- (3) Disciplined Approach. A disciplined approach was developed, documented, and used to analyze the selected programs. (Ref. Appendix B and IDA Record Document D-26.)

A detailed description of the study organization, participants, methodology and program selection process is contained in Appendix A. Appendix B documents a disciplined approach to planning and analyzing weapon system programs developed and used during the course of this study. The Electronic and Mechanical Weapon Systems Programs were reviewed, analyzed and the results detailed in Appendixes C and D, respectively. Appendix E expands on the diagnostics conclusions in this report and examines diagnostics requirements. Other subject areas such as affordability and test assets issues were analyzed and those results are in Appendix F. Information System Observations are contained in Appendix G and finally, Appendix H is a collection of the official data used to analyze the various parts of program structure during the course of the study.

#### IV. CONCLUSIONS, OBSERVATIONS AND FINDINGS

Numerous findings and observations resulted from the case studies. This section will highlight the most significant. Major conclusions from the case study analysis are:

- There are high-payoff actions currently known that must be planned for and retained in the weapon system acquisition process and programs. These include:
  - Changed management practice to reflect inter-dependencies in acquisition programs
  - Greater use of reliability design tools and processes particularly computer-aided design (CAD) and environmental stress screening (ESS)
  - Establishing "Off-Line" maturing of key technology including comprehensive R&M growth and maturation programs in the acquisition process and
  - Increasing fundamental work in all areas of diagnostics development
- Accurate and detailed engineering quality information on system and component failures must be provided for identifying and solving equipment problems and focusing technology efforts.
- Actions to enhance and expand R&M knowledge and experience of DoD and industry engineers and managers must be taken to achieve long-term improvement for the full range of weapon system acquisitions.

## A. HIGH-PAYOFF ACTIONS

The individual observations and findings for each of these areas are presented as follows:

### 1. Structure to Manage Interdependent Program Elements

a. Observations: The R&M elements of the acquisition process are well-known; however, the interrelationships and dependencies of elements and subelements are less well understood. As a consequence, management decisions have traded away R&M program elements for dollars and/or schedule savings which ultimately lead to costly overruns, schedule delays and downstream logistics problems.

Because of the much publicized problems in reliability, readiness and support, DoD put improvements in this area high on its priority list. The Carlucci initiatives (Fig. 2) directed at reforming the acquisition process gave reliability and support considerations a very high priority. As a result there has been a major increase in DSARC and top management attention. On each major program there is visibility at the top on progress in meeting R&M objectives through development, production, and in early field experience.

The track record from these efforts is uneven. Many of the more mature technologies have done relatively well in meeting reliability objectives. Newer, fast developing technologies often have serious problems, however, as do programs with accelerated or compressed schedules. The latter are becoming more frequent due to the Administration objectives of fielding new hardware faster. Thus there is a major challenge in leadership to manage acquisitions on accelerated programs so as to attain desirable R&M objectives. Technology advances are potentially helpful in such areas (e.g., in electronics) by providing opportunities to improve both performance and R&M provided the problem is attacked in both the technology base and the acquisition process.



INITIATIVE NO.	DESCRIPTION
9	IMPROVE SYSTEM SUPPORT OF READINESS
12	PROVIDE ADEQUATE FRONT-END FUNDING FOR TEST HARDWARE
16	CONTRACTOR INCENTIVES TO IMPROVE RELIABILITY AND SUPPORT
21	DEVELOP AND USE STANDARD OPERATIONAL AND SUPPORT SYSTEMS
30	PROGRAM MANAGER CONTROL OVER LOGISTICS AND SUPPORT RESOURCES
31	IMPROVING RELIABILITY AND SUPPORT FOR SHORTENED ACQUISITION CYCLE

FIGURE 2. Carlucci Initiatives for Improving the Acquisition Process that Impact R&M

A simplified view of the overall program process is shown in Fig. 3.

Key elements to this overall process are:

- Defining what is really needed.
- Providing sufficient and timely resources.
- Utilizing good design, manufacturing and testing practices.
- Providing timely and accurate feedback in the total process and taking action to identify problems and effect solution.
- Providing rapid and/or flexible change processing to permit problem resolution.

b. Findings: The management challenge posed by the inter-dependency issue is to structure a single acceptable disciplined approach to planning programs to assure balanced considerations of performance, budget, schedule and supportability. Once programs are so structured, the discipline must provide for continuing analysis and monitoring to assure that the appropriate balance is not lost as the program progresses through its various phases.

This disciplined approach must also recognize the dependency relationship among the program elements. For example, good reliability predictions depend on a good definition of how the hardware will be used and subsequently, a good environmental analysis. These dependencies result in many elements being "necessary" but few (or none) being "sufficient," in and of themselves, to achieve satisfactory or ultimate performance. The structured process may have more than one path to success but numerous paths exist

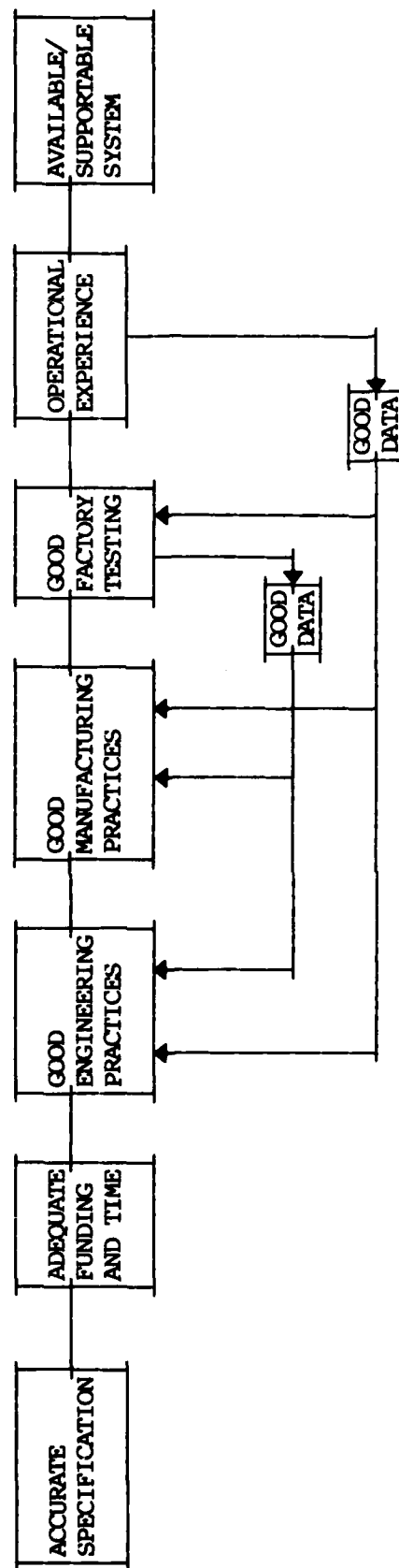


FIGURE 3. Simplified Program Process

that will lead to problems that will result in unsatisfactory reliability or maintainability.

c. Action: The Services should analyze and develop a discipline of managing interdependent program elements, including appropriate data bases and parameters, and include these in their acquisition strategy.

## 2. Reliability Design Tools and Processes

a. Observations: Design actions must identify and balance the stresses on various elements of the equipment. Reliability design tasks include environmental estimation, stress analyses, part selection and part derating. These tasks, in combination, define (or estimate) the operating environment of the equipment, predict the stress on the individual part or component, select a part that can operate effectively in that environment and, in the case of most electronics items, derate the part to provide a margin of safety between the rated stress and the estimated operating stress. These activities are fundamental to producing a reliable design. CAD has the potential to make R&M a part of the mainstream design engineering by including R&M as a design requirement and having integrated R&M design capabilities.

Even if R&M design procedures are improved it must be expected that most types of manufactured items will initially have some part and workmanship defects. To prove out manufacturing processes before fielding, environmental stress screening (ESS) is needed. Even if R&M design procedures are improved it must be expected that most types of manufactured items will initially have some part and workmanship defects. The ESS approach is to apply thermal, electrical and mechanical stress to precipitate failure of the weak parts and assemblies in the factory and thereby result in improved reliability in field use. All the electronics programs in the case studies used ESS to some degree (see Fig. 4). There was considerable variation in the details

	F-15 RADAR	F-16 RADAR	F/A-18 RADAR	FIREFINDER RADAR
PARTS	IC's & HYBRIDS	IC's & HYBRIDS	IC's & HYBRIDS	IC's & HYBRIDS
MODULE	YES	YES	YES	CONSIDERING
UNIT (OR BOX)	YES (4 OF 9 LRUs)	YES (1 FAILURE- FREE CYCLE)	YES (3 FAILURE- FREE CYCLES)	SELECTED UNITS
SYSTEM	YES 24 OP HRS (3 FAILURE- FREE CYCLES)	NO	YES 25 OP HRS (5 FAILURE- FREE CYCLES)	YES 100 HRS (25 FAILURE- FREE CYCLES)

FIGURE 4. Stress Screening Use

○ ARN-84 TACAN		
FIELD MTBF	200	(Before ESS)
FIELD MTBF	2000	(After ESS)
○ DEPOT REPAIR COST AVOIDANCE \$5M/YR		
○ SPARE REQUIREMENTS REDUCED		
○ UNIT COST OF EQUIPMENT TO SERVICE UNCHANGED		
○ YEARLY REPAIR SAVINGS = 6% OF PURCHASE PRICE		

FIGURE 5. ARN-84 Reliability Improvement due to ESS

of the applications, but all programs benefited through improved reliability. Other studies have shown that ESS reduces manufacturing costs and significantly improves productivity because of reduction in rework and associated retesting. Dramatic increases in operational reliability due to ESS, some more than 10 to 1, were also documented (see Fig. 5).

b. Findings: The findings for ESS and CAD are as follows. The design system needed is computer-aided design (CAD) supported by an R&M data base and tied to computerized R&M and logistics analyses. Integration of R&M tools and analyses into CAD will provide design engineers the disciplined use of specialized knowledge in real time with potentially dramatic reductions in cost.

In much the same way the integration of computer-aided manufacturing (CAM) with CAD can enhance both design and manufacturing. Integrated CAD/CAM can provide designers with knowledge of manufacturing constraints which can lead to a more consistent production process.

Development of an ESS approach should begin during the design phase and continue during the development phase. ESS should also be used on test hardware so that expensive tests are not delayed due to design and workmanship problems. Results should be analyzed to provide information needed to refine screens prior to beginning production. The ability to adjust, add or delete screens is necessary to achieve the ultimate ESS benefits.

ESS applied during early production serves as a "find-and-fix" program in which manufacturing process problems and some latent design deficiencies are identified and corrected. Stress screens should be determined after consideration of the process controls which can prevent introduction of manufacturing defects and after evaluation of test and inspection approaches. Stress screens should not be used in lieu of possible preventative action, since preventative action is almost always less expensive and usually results in a more reliable product.

The reliability potential of ESS is so significant that it warrants special attention. All electronics development and production programs should require ESS. ESS applications should be described in a plan and must be dynamic in nature and structured so that maximum screening effectiveness is obtained. Cost models, yield and rework data and failure data should be maintained to demonstrate effectiveness of the program. Periodic reports showing the status of screening results should be provided to management.

c. Action: DoD should invest in CAD systems and in ESS approaches that address R&M problems in order to mature and understand their use. Demonstration programs should be selectively funded and carefully evaluated. Also, a policy should be formulated to ensure ESS is applied to all acquisitions.

### 3. "Off-Line" Maturing of Subsystems and Components

a. Observations: Within a total weapon system program context, the off-line maturing of system and subsystem elements offers significant risk reduction for today's concurrent program environment. The T700 engine program represents a classic example of successful off-line development and insertion into a program with provisions for maturation (see Fig. 6).

b. Findings: In addition to this observation from the T700 program, the technology portion of this study recommended three essential features of "off-line" maturing that are re-emphasized here. The first is that a set of technologies should be matured in a manner which reflects their interdependencies. Second, the target chosen to provide the measure of success should be as realistic as possible, if not improvement to an existing system. Third, the results achieved should be generalized and become the new level of acceptable performance.

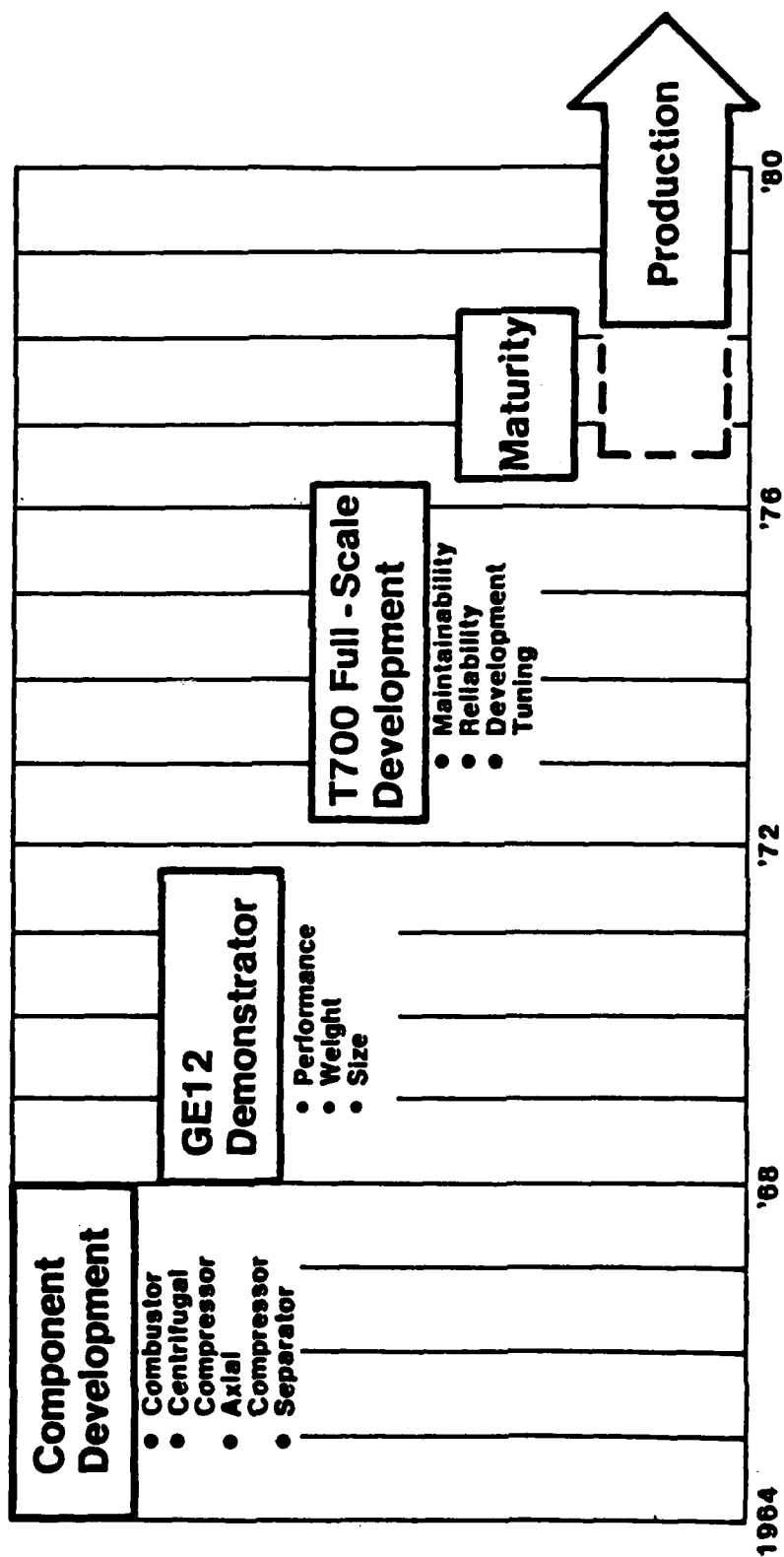


FIGURE 13. T700 Engine Evolution

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From a programmatic point of view, the management issue becomes one of when is the technology ready for program insertion and what actions will minimize the risk of doing it. There is no simple answer for these questions but the integrated approach to technology maturation discussed in Volume IV, Section V, coupled with evolution of the disciplined structured approach as discussed in Volume III, Appendix B, could result in a significant reduction in risk for new programs.

c. Action: The need for off-line component and subsystem development should be evaluated on each DSARC program as well as on less major systems. Guidelines should be developed for concurrent programs to routinely fund such developments.

The Services should also increase their technology base efforts for programs with objectives such as the Air Force ultra-reliable radar program.

#### 4. R&M Growth and Maturation

a. Observations: Without exception, the case studies showed that despite the best design efforts, problems will be found in development testing, production, and in field use. An example from the APG-66 program is typical (Fig. 7). These facts support the rationale that testing and growth programs are essential elements to producing reliable equipment. R&M growth programs should be oriented to supplement effective design and manufacturing processes.

A comprehensive growth and maturation program is more than just a test phase labeled reliability growth or reliability development testing. It is a coordinated effort starting in the conceptual phase, influencing the design phase, reaching across the whole test program and extending a reasonable period of time into field use. A well-executed growth and maturation program

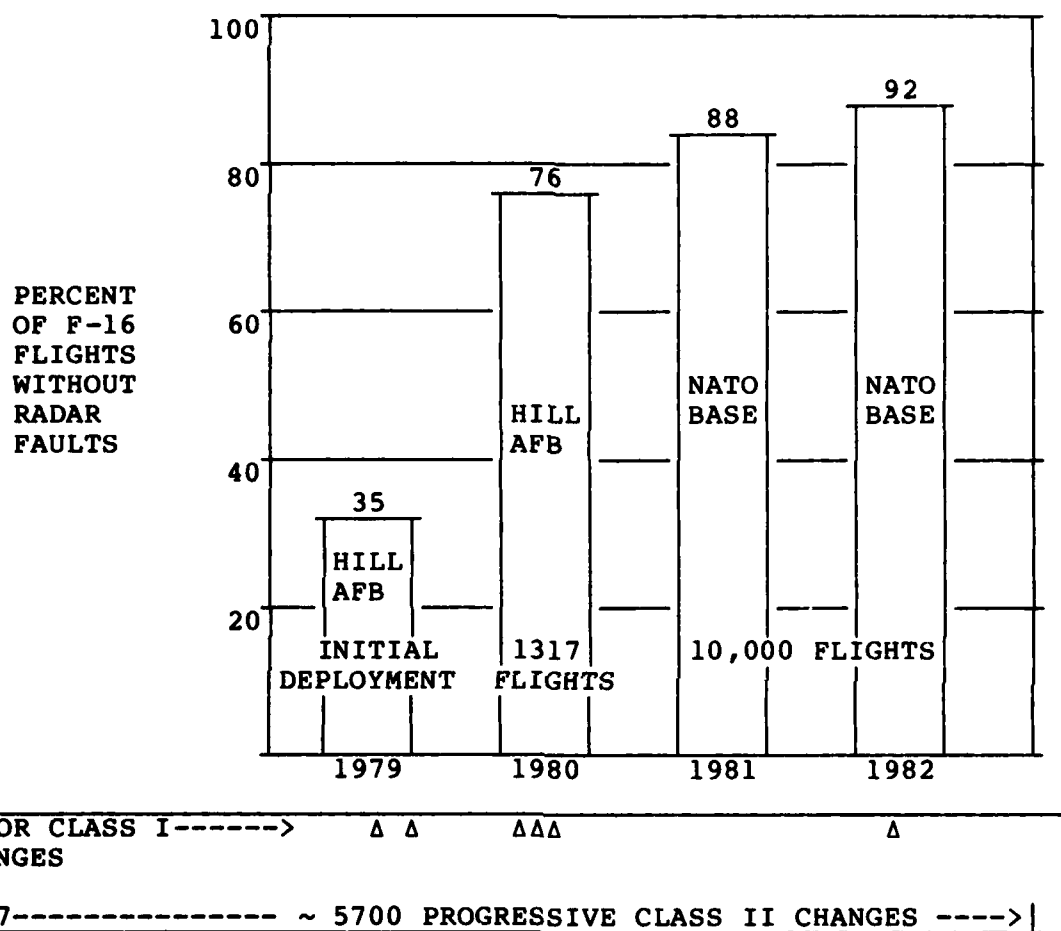


FIGURE 7. Changes Made After Fielding Significantly Increased the Percent of Flights Without Radar Faults

requires adequate resources for data gathering, data review and analysis, and for engineering manpower assigned to investigate, resolve and correct problems as well as an expedited change processing system to allow rapid incorporation of problem corrections.

It is essential that built-in test (BIT) development be structured to have a parallel growth and maturation program (see p. IV-21 for diagnostics observations). The BIT in all of the cases studied required a period of concentrated maturation before the BIT performance reached an acceptable level.

It is clear from some programs reviewed that additional classes of problems occur when equipment enters production and again when it enters operational service (Fig. 8). These problems must be identified and corrected, or the system will be plagued with the problems for its entire operational life. The continued growth and maturation of the equipment requires technical personnel with understanding of the design. The assignment of contractor personnel to the early operational sites can have a significant payoff in the continued growth and maturation process.

b. Findings: A comprehensive R&M growth/maturation program starts early in the conceptual planning phase, continues through the design phase, influences component development testing and continues into the operational phase. The programs evaluated in these case studies showed only a limited amount of growth planning and testing. The reliability improvement warranty (RIW) programs on the APG-66 and the LDNS were the only planned efforts that extended for any significant time into the operational phase. The following sections will provide perspective on the front-end design effort and the plans necessary to manage a growth program adequately.

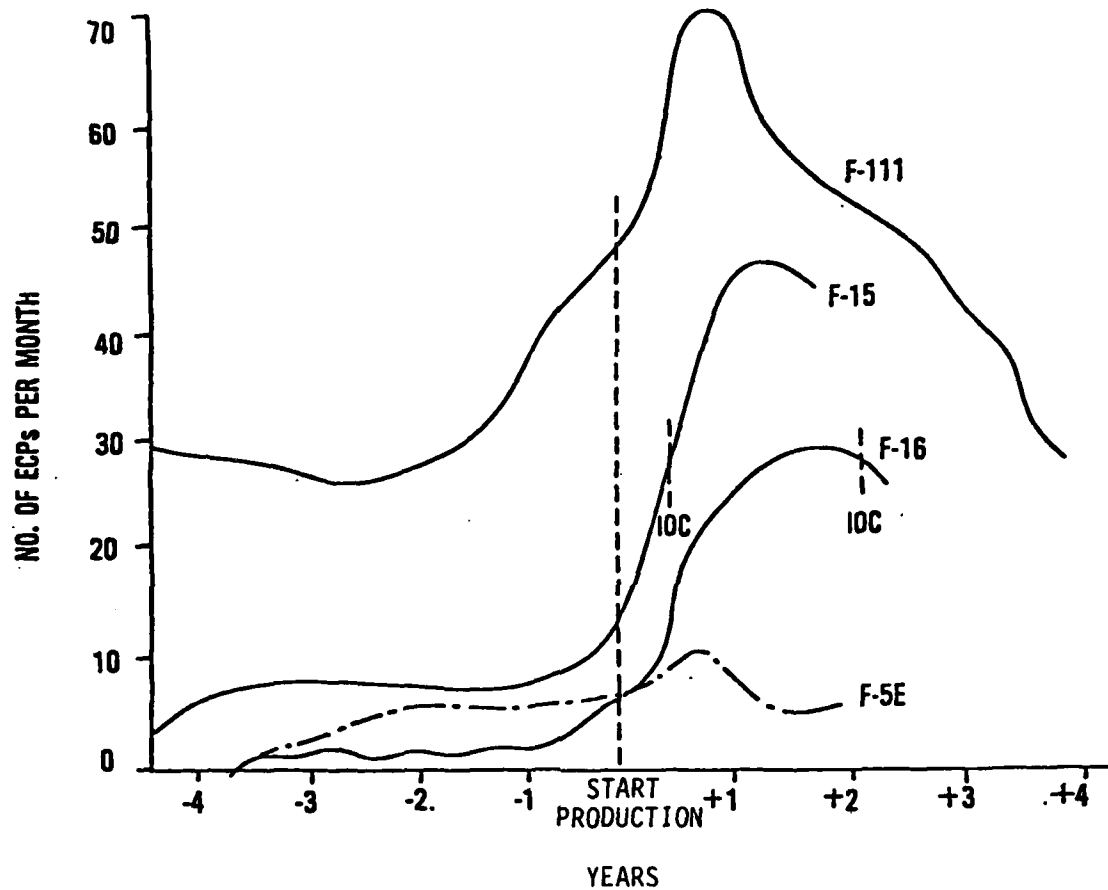


FIGURE 8. Engineering Change Proposal Rate

(1) Front-End Design Efforts for R&M

Appendix B of this volume identifies the structure for designing R&M into weapons system programs. The R&M elements identified were considered, to various degrees, in all the case studies evaluated. It is generally concluded that both the military and industry know how to apply these elements to achieve a high level of "designed in" R&M although this effort by itself will not yield the R&M potential of the system (see Fig. 9 for summary of design analysis).

System complexity generates problems which cannot be identified by analysis only. These complexity problems arise from (1) variations in the design environments from actual operational environments, and (2) constraints on resources to accomplish an accurate detailed analysis.

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	F-15	F-16	F/A-18	FIREFINDER
Reliability Analysis	✓	✓	✓	✓
Maintainability Analysis	✓	✓	✓	✓
Thermal Analysis	✓	✓	✓	✓
Stress Analysis	✓	✓	✓	✓
FMEA	✓	✓	✓	
Sneak Circuit Analysis			✓	(Antenna ✓ (Trans- ( & Power (mitter) (Supplies)
ORLA	✓	✓		
BIT Effectiveness	✓	✓	✓	✓
Testability	✓	✓	✓	✓

---

FIGURE 9. Design Analysis Techniques Summary

The integration of the total system gives rise to interactions between subsystems that are not identifiable prior to system integration. These interactions include the interplay with other hardware systems, and software. Software itself can create problems that are difficult to identify. Diagnostics falls into this category and a considerable testing effort is needed to perfect a system to the point that it demonstrates a minimum number of false indications of failure. Results from the case studies indicate that the front-end design effort led to higher levels of R&M at the start of the test phase.

(2) Management Environment for R&M Growth

DoD policy should and contracts should provide for integrated R&M growth programs with proper incentives for R&M growth. For major acquisitions, DoD policy should include planned operational R&M maturation including provision for on-site contractor design engineers, to investigate R&M problems and to provide the detailed information necessary to develop solutions. Acquisition programs must improve their responsiveness to engineering change procedures (see Fig. 10 for variances in flow duration). Imposition of customer control of the change process should be delayed as long as is practicable. Guidelines should be developed for tailoring management of ECPs during the R&M change introduction process. Guidelines should be taught to managers and enforced at all levels. Programming and budgeting should include resources for data collection, analysis, design of fixes, and verification during the production phase.

To achieve the R&M potential of a system, a structured growth program must be planned to begin early in the program. This planned program must include the identification of the reliability target, the number of test assets and phases considered

<u>PROGRAM</u>	<u>AVERAGE FLOW CALENDAR DAYS</u>
E-3A	344
E-4	210
ALCM	164
Roland	178
LDNS	5-30
CHANGE INITIATION THROUGH CONTRACTUAL APPROVAL	

FIGURE 10. Duration of ECP Approval Cycle

necessary to reach this potential target and consideration of the hardware generation to be used in each phase. Up-front planning is necessary to assure that adequate resources are made available and that program management understands the process to be followed. The general procedures in managing a growth program are defined in MIL-HDBK 189, "Reliability Growth Management." A similar requirement for structured approach exists for diagnostics which has a combined hardware and software system growth requirement.

The growth must start with the beginning of hardware testing and extend two to three years into field operation. A typical growth profile is shown on Fig. 11. A test-analyze-and-fix philosophy must prevail throughout the program. Each phase must make efficient use of the test resources. After each phase the impact of corrective actions is evaluated and a management decision made regarding the adequacy of the test phase with repeat testing on corrected hardware as a possible outcome.

An accurate and timely failure feedback procedure must be established to provide the designer the necessary information to accomplish the required corrective action. During early field operation this will require on-site engineering support. This on-site support is necessary to ensure accurate information of the failure causes to support redesign.

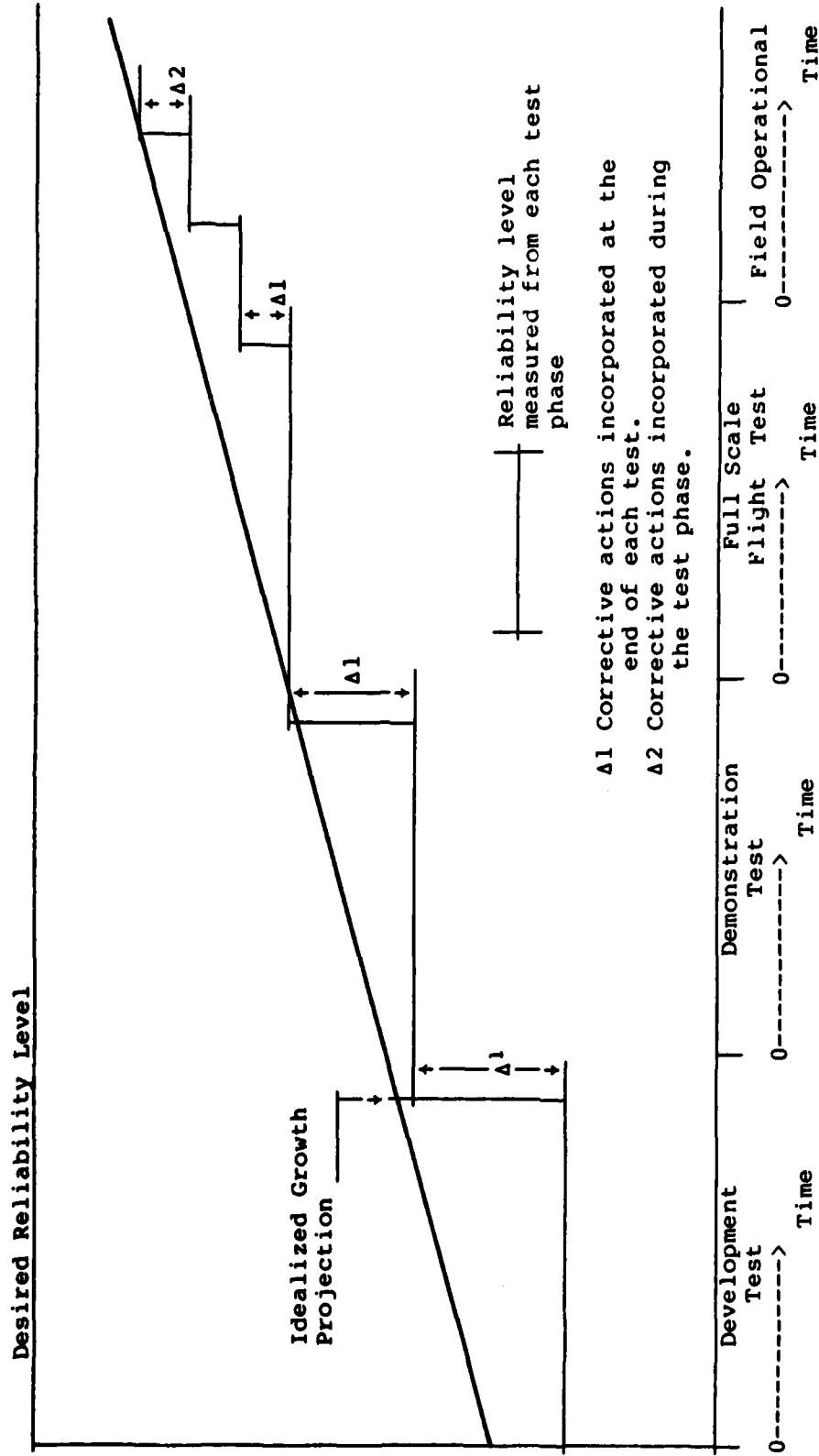
A prime requirement to ensure timely corrective action in the field operation phase is a rapid ECP process. In today's environment it sometimes takes as long as two years or more before a corrective action will get into the hardware. Methods for speeding this process must be an integral part of the growth/maturation phase.

Once the potential levels have been achieved the system must be monitored to prevent them from degrading during production and/or changing field environments.

### (3) Maturing the Support

Today's complex, highly-interactive systems require the growth and refinement of other factors to realize the full potential of reliability and maintainability. These factors include: diagnostics, manpower and human factors, training,





$\Delta 1$  Corrective actions incorporated at the end of each test.  
 $\Delta 2$  Corrective actions incorporated during the test phase.

FIGURE 11. Typical Growth Profile

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technical data, support equipment, and software. The complex interactions of man-machines-systems result in the readiness and sustainability of military systems. Very significant differences in readiness and sustainability can be derived if the total support structure is matured in a systematic way. Growth and maturation programs must be thought of in this broader context.

#### (4) Funding

The growth and maturation program for reliability and diagnostics is critically dependent on front-end funding, which must be structured with full identification of the activities discussed above and with particular attention given to adjunct test hardware.

A conceptual view of current versus needed funding profiles is given in Fig. 12. Further analysis would be needed to define the details of an actual funding profile; Figure 12 is intended only to visualize an apparent current problem.

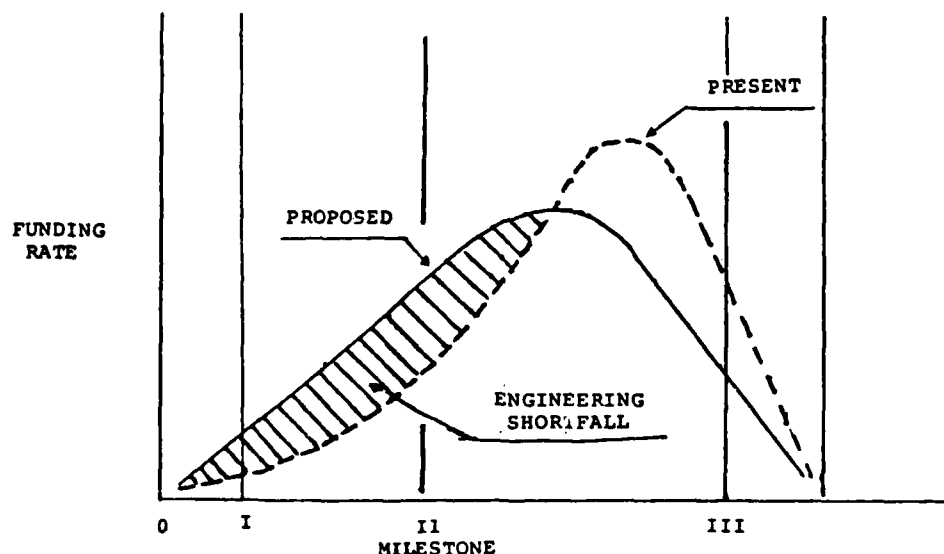


FIGURE 12. Funding Profile for RDT&E

c. Action: R&M Program MIL-Standards should be revised to include a plan for an integrated development and field R&M growth plan.

## 5. Diagnostics

a. Observations: Diagnostic systems development is an immature discipline when compared to reliability. In diagnostics, there are no accepted definitions of requirements that can be used for contracting that are directly understandable to a designer and that can be related to field performance. On the other hand, for reliability, there are design tools for analysis of the stresses that cause failures as well as for predicting failure rates of components, subsystems and systems. Design tools for diagnostics are much less structured and practiced.

In reliability testing, there are proven techniques for simulating the operational stresses an equipment will undergo, weeding out the causes of unreliability and verifying the potential system reliability. Diagnostics testing techniques are much less mature. Though fault insertion tests are performed in the lab, they are poor predictors of field performance. A comparison of results from laboratory fault insertion tests and field operational tests is shown in Fig. 13. It will identify some problems, but success in such a demonstration is no guarantee of a good design. Thus, demonstration by fault insertions are necessary, but not sufficient, to validate a diagnostics design.

During the early operational life of a system the assessment of reliability performance is much more straightforward than diagnostics performance. While there are problems using field data to assess reliability, such data does provide some management information and can be used for trend assessments.

# MULTIPLEX BUS EQUIPMENT

MEASURE OF EFFECTIVENESS	RESULTS		RATING	
	FAULT INSERTION TEST	FIELD	SATISFYING CONTRACTUAL REQUIREMENTS	AS USER SEES IT
FAULT DETECTION (%)	90	49	SATISFACTORY	DEFICIENT
CANNOT DUPLICATE (%)	--	45.6	--	DEFICIENT
FAULT ISOLATION (%)	93	69	SATISFACTORY	DEFICIENT
RETEST OKAY (%)	--	25.8	--	DEFICIENT

# FLIGHT CONTROL SYSTEM TEST (ST)/BUILT-IN-TEST (BIT)

MEASURE OF EFFECTIVENESS	RESULTS		RATING	
	FAULT INSERTION TEST	FIELD	SATISFYING CONTRACTUAL REQUIREMENTS	AS USER SEES IT
FAULT DETECTION (%)	100	83	EXCELLENT	DEFICIENT
CANNOT DUPLICATE (%)	--	17	--	DEFICIENT
FAULT ISOLATION (%)	92	73.6	--	DEFICIENT
RETEST OKAY (%)	--	20	--	DEFICIENT

Source: IDA Paper P-1600, Built-in-Test Equipment Requirements Workshop

FIGURE 13. Typical Fault Insertion Test Results versus Field Results

Such maintenance data systems are, however, not useful for diagnostics evaluation purposes, since the data does not reflect the method of fault detection/isolation, human intervention in the decision process, or troubleshooting time factors.

Lack of knowledge in the diagnostics area (contracting, statement of requirements, design, testing, deployment) presents a significant challenge to the development community to improve diagnostics of current weapon systems and acquisition methods for improved diagnostics in future weapon systems. Fundamental work is required in all these facets of weapon program development to produce acceptable diagnostic capabilities for field use.

b. Findings: From the case study activities and numerous other studies and presentations reviewed, it is clear that the achievement of a mature diagnostics capability is the result of a defined process. This process encompasses both research and development activities, which are not weapon program specific, as well as the acquisition process, which can be weapon program specific. Achieving effective diagnostics requires a plan, management strategy, motivation, technical activity, and funding that spans system acquisition from initial requirements definition through deployment.

(1) Statement of Requirements

The military user's requirements should address diagnostic capability in the larger context of the operational mission and environment as well as the support constraints of manpower, the skill-level maintenance concept, deployment, and the logistics burden. The requirements, constraints, environment, and economics should then drive the architecture of the system, diagnostics being one of the fundamental characteristics. Significant information improvements are needed for formulating these requirements.

There are a number of innovative Service efforts to define requirements and development objectives for readiness and support at the front end of a weapon program. Examples include the Air Force Advanced Tactical Fighter (ATF), the Navy Submarine Advanced Combat System (SUBACS), the Army Mobile Protected Gun System (MPGS), and the Joint Services Advanced Vertical-Lift Aircraft (JVX). Figure 14 summarizes the kind of performance-driven support requirements and constraints which define the context for generating diagnostics requirements. Objectives which call for reduced levels of maintenance, high utilization rates, self-sustaining operations and reduced support tail should drive the development of high-confidence built-in-test with CND/BCS/RTOK rates of near zero.

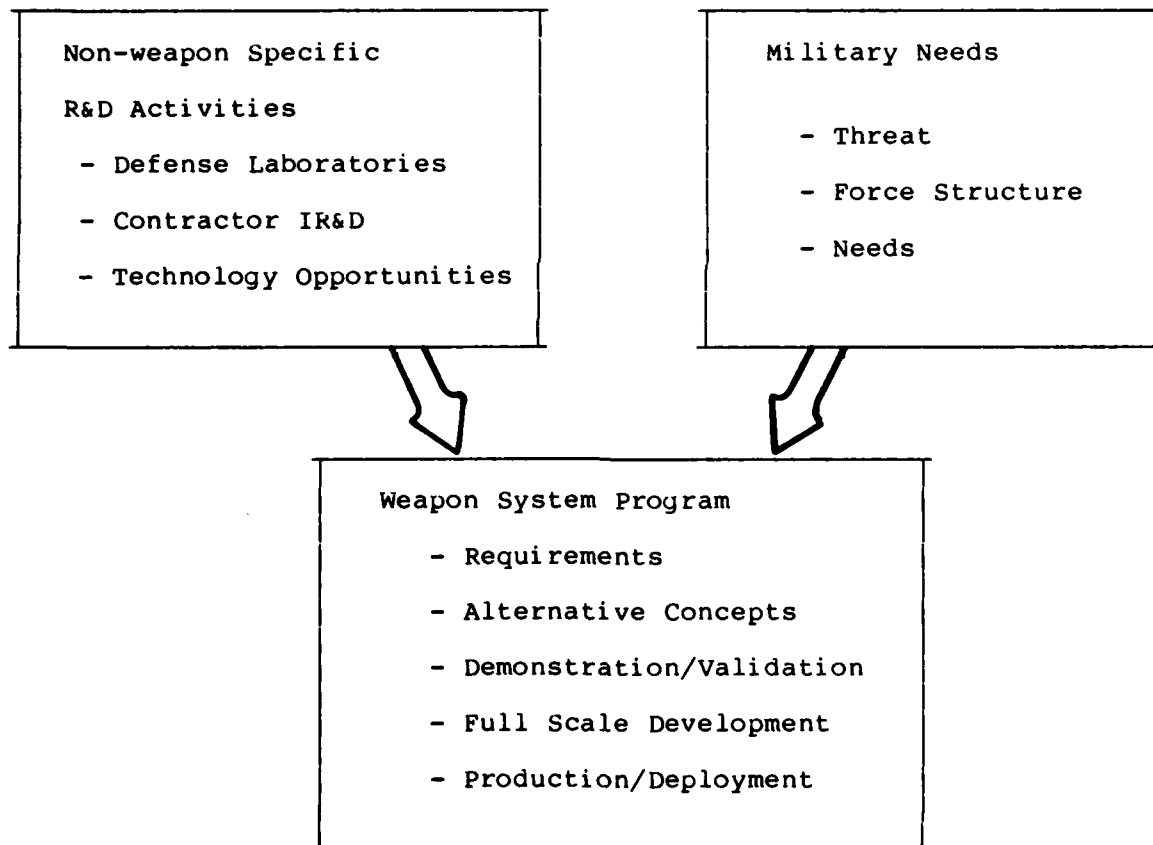


FIGURE 14. Diagnostics Context

Definitions, terminology, and figures of merit to describe diagnostics requirements have proliferated to the point that communication relative to diagnostics measures is difficult. This is not a trivial problem; it impedes the way diagnostics are specified, managed, designed, tested, and measured. Proposed MIL-STD-XXX, "Testability Program for Electronic Systems and Equipment," and MIL-STD-1309 are useful but not sufficient steps to resolve this problem. Better ways of specifying diagnostics requirements are needed to achieve the readiness and support goals of the Services. One proposal was reviewed which appears to have the capability of influencing reliability, maintainability, support costs, and readiness in a manner to achieve a two-level maintenance capability. The approach specifies that all avionics line-replaceable units meet a specific threshold of acquisition cost per removal-free operating hour. This parameter has the advantage of being operationally useful and measurable in the field though it may not communicate requirements clearly to the designer.

## (2) Design

In the area of diagnostics system design, the following needs have been identified:

- a. Strategies to minimize cannot duplicate (CND), bench-checked serviceable (BCS), retest OK (RTOK), and false alarm conditions during design.
- b. Techniques to maximize vertical testability.
- c. A flexible diagnostic system so that changes can be incorporated readily in diagnostic algorithms, screens, and tolerances with minimal hardware impact.

- d. Fault-free software development techniques.
- e. Techniques to enable more concurrent hardware and software development and earlier integration of the two.
- f. Trade-off tools for assessing the diagnostics implications of design decisions on the support structure.
- g. Computer-aided engineering techniques for enhancing design for testability in support of proposed MIL-STD-XXX. (Some techniques such as LOGMOD and STAMP may already be able to meet this need, though they are not widely used.)
- h. Both the Services and contractors need to develop experienced people who understand how to achieve good diagnostics designs.
- i. Tools for predicting, measuring, and managing the diagnostics designs.
- j. Better design practices such as control of timing margins in high-speed circuits and systems.

(3) Development and Demonstration Test

Improvements in development and demonstration testing will aid diagnostics development. The following measures have been suggested by experts in the field:

- a. Use reliability and other test events as opportunities to discover problems with BIT performance.



Environmental testing may be particularly useful for discovering false-alarm indications such as induced intermittents and transients.

- b. Increase the number of spare assets and the time budgeted in the system integration laboratory to investigate diagnostic anomalies without impacting the schedule and use of other assets.
- c. Expand the set of faults inserted. (Time required for fault insertion tests might have to increase.)
- d. Increase the allowable cost of demonstrations to include repair costs. This action will permit the insertion of a better cross-section of faults.
- e. Develop a library of computer simulation models to test BIT (hardware, software, firmware).
- f. Adopt comparability analysis as a useful tool for identifying a realistic fault set for insertion.
- g. Develop and incorporate in MIL-STD-471 improved demonstration techniques to predict field diagnostics performance.

#### (4) Operational Test and Field Maturation

Field maturation is essential to achieve inherent diagnostics potential. When a system is first fielded, it is common to find that not all the hardware and software provisions of the diagnostics have been fully implemented. In addition, the operational use patterns and the environment produce new failure modes and diagnostics indications. These new indications,

which the BIT may not deal with properly, are resolved by the judgment of operators and maintainers (who may not have been trained to deal with them) with the aid of technical data (which may not have been developed to address them). A structured diagnostics maturation effort is the only way most experts see to bring the diagnostic capability to its full potential. The APG-65 and APG-66 programs are excellent examples of effective BIT maturation. Figure 15 indicates the rate of diagnostics growth of the APG-66 radar during the FSD/production phases. The key features of these programs should be used in structuring future maturation efforts for complex equipment.

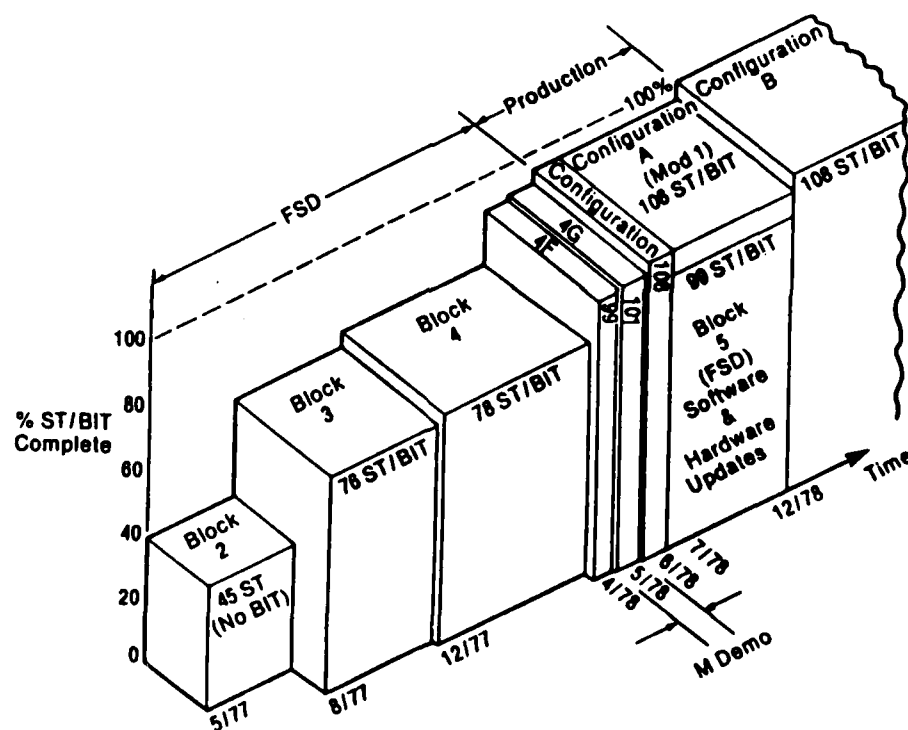


FIGURE 15. APG-66 Radar ST/BIT Growth

The key features of such a diagnostics maturation program are as follows:

Planning: The program office, prime and subcontractors, the user, the operational test agencies, must accept the fact that complex systems require diagnostics maturation in the operational environment. This recognition must be coupled with commitment, funding and a management plan to pursue diagnostics maturation until a mature capability is clearly demonstrated in the intended operational environment. The schedule for this effort is dependent on many factors. The APG-66 took 20 months to grow to full test implementation and was followed by another 24 months of maturation. The APG-65 schedule spans 34 months.

Data Collection: A special diagnostics data collection and analysis system is required to capture information on failure occurrences and causes in enough detail to provide a credible data base for developing and implementing engineering solutions. The Navy 3M and the Air Force MDCSs are not sufficient but can be useful for this purpose. The inputs needed include the specific failure indications and circumstances logged by the aircrew/operator, a BIT debriefing for all missions, the specific indications of detection and methods of isolation, a specific serial number track of LRUs/WRAs through the ultimate repair action and subsequent performance after repair, as well as the elapsed time for each element of the maintenance event (set-up, troubleshoot, repair, verification, teardown). Analysis can then focus on the causes of alarms, CNDs, BCSs, no defects and lengthy repair times.

Recorders: If the system does not have built-in capability to capture the detailed environmental condition information at the time of failure indication, additional sensors and recorders should be installed on the system during the maturation phase to provide this information.

Engineering Manpower: Knowledgeable design engineering personnel are essential at operational locations to observe and analyze the performance of diagnostics capability so that problems can be recognized quickly in context with the operational environmental variables.

Maintenance Manpower: A team of operational maintenance personnel (user, supporter, tester) must be available and motivated to mature the diagnostics and to institutionalize preferred troubleshooting procedures and maintenance policy.

Operational Support: The operational entity which is employing the new system must support diagnostics maturation. When a system fails or exhibits a diagnostic problem the emphasis should be on understanding the cause of the problem rather than hurrying the system back into commission. Operational units designated for this activity must have sufficient assets assigned to meet both operational and maturation requirements.

Data Base Resources: Computer resources (time, access, programming) must be available at the operational location to maintain a diagnostics maturation data base and to support timely analysis.

Software Discipline: Since many BIT anomalies are corrected by software changes, a vigorous software data collection and tracking effort is required to update and control software configuration. Though this activity is normally conducted at the contractor's facility, it must interface closely with the field maturation effort. The APG-66 went through at least eight block-configuration changes and one major ECP during maturation. The magnitude of a typical software block-change is exhibited by Fig. 16 for the F-16.

<u>Configuration BIP</u>	<u>System Performance Patches</u>	<u>ST/BIT Patches</u>
Block 4A	157 Patches	42 Patches
Block 4B	31 Patches	9 Patches
Block 4C	25 Patches	7 Patches
Block 4D	17 Patches	9 Patches
Block 4E	85 Patches	34 Patches
Block 4F	16 Patches	10 Patches
Block 4G	0 Patches	3 Patches
Block 4H	32 Patches	6 Patches
Block 4I	35 Patches	11 Patches
Block 4J	7 Patches	3 Patches
Subtotal 405		Subtotal 134
Total 539		

FIGURE 16. FSD Software Modifications and Block Update Summary

Contractor Support Base: Contractor resources (time, engineering manpower, and system integration laboratory/software support facilities) are required to support the field engineering activity. These resources are necessary for verifying field anomalies as well as formulating, testing and implementing diagnostic corrective actions. Production testing activities at the factory may present other opportunities for observing additional failure modes and diagnostics indications. These opportunities for diagnostics improvements should be used to supplement the field maturation activity.

Contractor Use of Diagnostics: The contractor must be required to use the BIT, diagnostics procedures, and technical data being developed for Service use whenever he is performing maintenance; for example, during early flight testing and interim contractor support. These events present early opportunities for maturation, even before operational testing starts.

c. An Approach to Planning Future Avionic Diagnostics: In addition to the above activities, Appendix E includes an illustration of how a system might be structured to achieve significant diagnostic improvement. This approach is oriented specifically toward avionics, but the thought process should be useful for other applications as well. Regardless of the system type, diagnostics capability must be considered as a fundamental concern in the conceptual phase of system architecture development.

In the world of avionics diagnostics, bold steps are necessary to improve performance in the field radically and reduce substantially the cost of maintenance. Supportability improvements, particularly the contributions of avionics diagnostics, require new approaches to solve the problems faced by the Services in the field today. Technology improvements appear to

offer the opportunity to make strides toward such improvement. Advanced architectures provide the means to achieve improved supportability.

d. Action: An agency should be designated to be responsible for developing a structured process for carrying diagnostics through from stating requirements to design, development, test, and maturation. The most natural vehicle for this would be a diagnostic standardization program similar to those started for reliability in the last 10-15 year time period at both DoD and NASA. In addition, there is need to establish an R&D program to develop the technologies required to solve current problems (false alarm and unnecessary removals).

## B. INFORMATION

### 1. Conclusion

Accurate and detailed engineering-quality information on system and component failures must be provided for identifying and solving equipment problems and focusing technology efforts.

### 2. Observations

A thorough understanding of how each military Service operates and a comprehensive investigation and analysis of the sources of data are necessary if one is to avoid misinterpreting reported data. Wide variations in results, using data obtained from the same data base and reported in numerous studies and briefings, have been observed in the course of this study. Examples are provided in Appendix G. Based on analysis of these cases, the following findings were made.

## 2. Findings:

The planned operational concepts, as reflected in the Service Year-2000 studies, and the complexity of current and planned weapon systems, make it essential that data systems be capable of supporting units in combat as well as peacetime, and be user oriented (e.g., Automated Data Entry) for accuracy and speed. The Army SDC system provides a reasonable solution for management uses. The Navy (Air) has an excellent, very flexible query system. The Air Force AMS for C-5As is a superb system but currently only for C-5As. The Navy data system for submarines is very comprehensive and has paid for itself many times over; for example, providing engineering quality data to support decisions for the extension of overhaul periods. Additionally, all of the Services have good data systems which provide excellent data during the acquisition process. In many cases, however, the systems are not imposed on the contractor nor continued after the system is fielded.

The current institutionalized data systems are archaic. These systems are useful only to track trends and only then when (a) no significant data systems changes have occurred within the trending period and (b) no significant changes in operational scenarios/mission profiles have occurred in the trending period. Data system usage in studies like this one are fraught with problems because of the desire for quantitative backup for proposed changes/concepts, hence the requirement to use the data in ways that exceed the systems capabilities which leads to judgment based on incremental differences as well as other doubtful uses.

The current military data systems do not provide useful data that can be used to characterize the R&M performance of a given technology. For example, if one were to try to evaluate the impact of changes from currently fielded solid-state equipments to VHSIC implementations, it soon becomes rapidly apparent that the data base does not permit one to obtain R&M data at the device level, or by device type.

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Contractors and customers alike need engineering quality data in order to be able to correctly identify a problem and evaluate candidate solutions from both a cost and performance viewpoint. Additionally, it is desirable to be able to monitor performance of an item by serial number identity, so that the effectiveness of changes under the configuration control system can be evaluated. Under the current maintenance data systems this is difficult, since the data systems were not designed to provide such information.

The lack of good, easily accessible data to support the requirements process is a key reason for the shortfalls in the requirements process and can lead to unbounded optimism and very little useful input to the design process. Requirements documents for Service data systems do not include requirements for the kinds of data needed to support the acquisition (especially the R&M requirements) process. In most cases, the same kinds of data elements are required for yearly resource requirements calculations, e.g., replenishment spares, modification requirements, manpower, support equipment, etc. The case studies stressed the need for reasonable yet challenging R&M requirements. In order to accomplish this task, it is necessary to know the R&M performance of similar systems in the field, differences in the intended operational environment (mission profiles) versus the comparable systems, the potential impact of new or different technology, and how to translate field R&M parameters into useful inputs for the design process.

Service data systems have been used as aids for this process. The F-16 and F/A-18 programs both used comparability analysis to estimate requirements based on similar systems. One problem with this procedure relates to the previous discussion. The comparability analysis, by its very nature, usually presumes the status quo for any significant problems incumbent in the baseline system, e.g., masking real reliability and maintainability values due to

inadequacy in the support system (training, support equipment, diagnostics, etc.). There are notable examples where attempts to unmask these problems have occurred, e.g., estimated changes to F-16 radar removal rates if diagnostics-related false removals could be reduced to two percent. Detailed analysis of this type is not easy due to data inaccuracy and data availability. The data systems also fall short when it comes to assessing the impact of technology. They do not possess the accuracy and detail necessary to support such analysis.

Very detailed and often meticulous data collection systems, far beyond the capabilities of standard data systems, are required in order to provide the detailed data necessary to find and fix diagnostics problems. Current field data systems do not provide meaningful data that can be used to assess the performance of diagnostics systems (BIT, FIT, ST). Again, as in the case of hardware problem reporting, the existing data systems at best give top-level indicators, but no detailed information that can be used to assess the diagnostics performance--let alone any clues as to the real problem or root cause of failure--the information needed by engineering. In most cases on-board recording or monitoring of fault detection parameters is necessary in order to find, fix and verify problems such as intermittent failure indications.

There have been a number of independent short-term efforts to assess diagnostics capabilities on the F-15, F-16 and F/A-18 FOT&E/MOT&E programs, but these have relied on special data collection systems, each tailored to the specific needs of the program. The F/A-18 program includes a special (two-year) BIT maturation program during which special data collection requirements will be implemented.

Detailed, accurate data during the early operational phase of a weapon system program is critical to improving reliability, maintainability and readiness. The importance of R&M up-front in the design process cannot be overemphasized. The basic attention to, and stressing of, R&M principles allows the system to start

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from a reasonable posture. The front-end work does not, however, negate the need for a planned growth maturation phase; it lays the necessary foundation for growth and maturation. It is unreasonable to expect that all field problems are or can be found and fixed prior to operational use of the system. Diagnostics, again, is the toughest area to mature due to the interactions with all aspects of the support structure. Reliability is but one driver of diagnostics. Manpower, human factors, training, technical data, and support equipment all interact with diagnostics to increase the magnitude of the find and fix process. Unfortunately, many of these elements are not available for a total system assessment until the early fielding phase. Again, the limitations of normal service or contractor data systems make it necessary to add special adjuncts to the data systems.

The criticality of detailed accurate data in the early operational phase as well as the more broadly defined development phase cannot be overemphasized. In order to provide the types of data necessary to identify and fix early integration problems, operational reliability failure modes, fault detection anomalies, fault isolation problems, support equipment interface problems, need for additional technical orders and troubleshooting aids, need for additional training, etc., adjuncts to Service data systems such as those listed in Fig. 17 may be required.

In all cases the good data systems, discussed further in Appendix G, have one set of common attributes--they are designed and implemented so that the data are rapidly available and very useful to the person who records/reports the data. Given the off-the-shelf capabilities available today in information and communications technology and the extremely high payoff in readiness improvements, weapon system quality, productivity, O&S cost reductions, etc., demonstrated at Dover AFB, in the Navy submarine program, and by the Army SDC system, it is imperative that the highest of priorities be placed on developing and fielding state-of-the-art Service logistics data systems as soon as practical.

In Summary, contractors and customers require engineering-quality data in order to be able to correctly identify a problem

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ADJUNCTS TO SERVICE  
DATA SYSTEM CAPABILITY

USE/FUNCTION

Serial number tracking

- Tracking of equipment configuration
- Failure analysis
- Modification tracking
- Identification of bad actor equipment/components

Tracking capability for parametric BIT detection data

- Locate false alarm problems
- Identify intermittent failure problems
- Provide correlation information for fault detection and fault isolation
- Aid in tracking of vertical testability, i.e., system vs. intermediate and/or depot level test equipment

Provisions for incorporation/use of time-of-failure/failure indication

- Correlation of failures or indication to other factors, e.g., temperature, altitude, vibration, turn-on, etc.

Provisions for tracking software related R&M problems

- Provide for sorting software related problems from other types of R&M problems

Special assessment team including program office, test or user and contractor design/engineering support personnel

- User-contractor-SPO interface and contact with system design personnel to ensure the correct problems are identified, analyzed and fixed.

FIGURE 17. Adjuncts to Service Data Systems

and evaluate candidate solutions from both cost and performance viewpoints. Additionally, it is desirable to be able to monitor performance of an item by serial-number identity, so that the effectiveness of changes under the configuration control system can be evaluated. Under the current maintenance data systems, this is not possible since the data system was not designed to provide such information.

Detailed, accurate data collected during the early operational phase of a weapon system program is critical to improving reliability, maintainability, and readiness. It is unreasonable to expect that all field problems are, or can be, found and fixed prior to operational use of the system. Diagnostics, again, is the toughest area to mature due to the interactions with all aspects of the support structure. Reliability is but one driver of diagnostics. Manpower, human factors, training, technical data, and support equipment all interact with diagnostics to increase the magnitude of the find-and-fix process. Unfortunately, the impacts of many of these elements cannot be assessed until the early fielding phase.

### 3. Action

Develop and implement policy to ensure that funding and procedures are in place to get engineering quality data to support the planned maturation on specific programs which include R&M growth.

## C. EDUCATION

### 1. Conclusion

Actions to enhance and expand R&M knowledge and experience of DoD and industry engineers and managers must be taken to achieve long-term improvement for the full-range of weapon system acquisitions.

## 2. Observations

The cases studied showed that contractors do respond to perceived DoD priorities. One factor which contributed to contractor perception of the importance that DoD placed on R&M was the capability and knowledge of personnel the contractors interfaced with on R&M-related items. R&M have not always been given proper emphasis by engineers, support personnel, and managers. Managers and engineers must understand what the different elements of an R&M program are, how they are inter-related, and what they contribute to R&M success. Additionally, DoD engineers and management would benefit from having access to highly qualified, experienced personnel who could assist them at critical times during program development.

## 3. Findings

There are several facets to the solution of this problem. One of these is R&M training. R&M training is provided currently by a number of separate DoD Service Schools, contractors, and educational institutions, but it is fragmented and limited in scope. There is a real need to upgrade R&M training throughout DoD and industry.

The need for improved training methods results both from the fact that there is little formal academic means to obtain the basics of reliability and maintainability skills and that many, if not most, of the current DoD education programs do not provide adequate coverage of the basics necessary for a successful R&M program. Within the case studies, there was an apparent correlation between the assignment of experienced personnel and the relative success of the particular program. How this experience was gained was not examined.

Another facet in the solution to this problem is the establishment of a method of providing highly qualified, experienced "consultants" to the engineers and managers at critical times in the development cycle. Various attempts have been tried by the Services, from the review method such as the Navy Pre-Production Reliability Design Review (PRDR) and Air Force Independent R&M Reviews to more formal assistance teams. When experience is limited, efforts must be made to share it among programs.

One conclusion is that the content and results of the case studies could be used to materially enrich existing educational programs within the DoD. This would not only improve the skills of the R&M and engineering practitioners, but also form a basis for educating program managers and acquisition management executives in the ramifications and implications of the various alternative structures for a successful R&M program.

a. Improving the R&M Capability in DoD. The current DoD work force has not received sufficient training or support in R&M. Under current circumstances it does not appear likely that this condition will change in the future. In fact, the problem is likely to become more serious as technology becomes more advanced.

Fundamental needs for improving the DoD R&M work force competence and performance are divided into four categories--development of DoD work force capability, development of an in-house advice and assistance capability, improvement of contractor relations, and interface with the academic community.

- (1). DoD Work Force Capability. Development needs for the DoD work force capability for R&M fall into three general categories. These categories are training of engineers and scientists, training for personnel in ancillary functional areas, and managerial training.

There is a critical need to upgrade the competence of the DOD military and civilian work force in the design aspects of R&M. Existing training programs emphasize programmatic or mathematical aspects of R&M and have too little coverage of those design engineering techniques that have an impact on the actual R&M of the equipment. Existing quantitative training is patterned largely after the standard quantitative textbooks that tend to be theoretical rather than practical. The DoD R&M work force should be provided quantitative skills which are relevant to the R&M functions performed. R&M training should incorporate appropriate engineering methods and techniques. The engineering world is one of constant change. Therefore, the DoD R&M training program must be dynamic and include courses in development of system R&M requirements; management of the acquisition process to optimize system effectiveness and readiness; R&M program management; R&M engineering management; design for R&M; production R&M assurance; software impact on R&M; and R&M testing and evaluation.

There is also a critical need for managerial training in such areas as reliability, maintainability and readiness. R&M training for managers can enhance the managers' decisionmaking capability. In addition, there would be a better understanding between design engineering and other management decisionmaking groups.

(2). In-House R&M Advice and Assistance Capability.

Within the DoD there are broad ranges of experiences from the "school of hard knocks" to successes.



Attempts to capture this experience have at best been superficial. The fact that attempts have been made demonstrates recognition of the need for consolidated in-house consultations and assistance capability.

Operational reliability and maintainability problems that are not solved at the source surface occasionally throughout the life-cycle. An in-house cadre of R&M engineering specialists (a quick-reaction team), that can be tasked on short notice to provide advice and assistance or independent opinions on day-to-day operational problems, is a possible solution worth exploring.

- (3). Government/Contractor Relations. Case study reviews have shown that best results were obtained through the mutual respect of government/contractor personnel working in a cooperative, non-adversarial manner. Likewise, within the government environment, similar cooperation and the ability to assess R&M activity are important contributors to improved R&M.

Most of the actual R&M engineering work for DoD is performed by contractor personnel. Government engineering personnel most frequently concentrate on: (1) developing, reviewing and assessing documents that prescribe R&M requirements to contractor engineers; and (2) reviewing the results of contractor R&M engineering activity. It is imperative that Government engineering and technical personnel be thoroughly versed in R&M engineering needs and related technology. Achievement of technical competence and respect is essential to fostering cooperation between Government

and contractor personnel and in evaluating the contractor's R&M plans.

- (4). Academic Relations. Most college and university engineering curricula concentrate on basic skills and disciplined knowledge. Only a few courses address R&M technology. There is a need for increased communication between the academic community and the R&M engineers and technicians. It is unlikely in the foreseeable future that fully adequate training and education in R&M technology will be widely available from the academic community.

b. Current Status of R&M Training and Education in DoD.

There are several education and training sources from which DoD R&M engineers may obtain or may have been obtaining job-enhancing technical and management skills, knowledge, and abilities.

(1). Academia. Formal college and university training specifically applicable to the needs of the DoD R&M work force is quite limited. However, some educational opportunities are available to the R&M work force. Some DoD installations have access to local university/college courses which will help to develop R&M-related skills. Though specific offerings vary between installations, individual courses and/or educational programs provide education in R&M subjects, such as reliability, system management, contracts and procurement. The education available is generally introductory in scope and does not provide the opportunity for in-depth education in R&M engineering techniques.

(2). DoD Technical and Professional Training. Within the Department of Defense, there are a number of schools that focus on the technical problem of acquiring new weapon systems.

- Defense Systems Management College (DSMC). The current curriculum of DSMC includes the 20-week Program Manager's Course, a 3-week Executive Refresher Course, and a 1-week Flag-Rank Refresher. These courses include R&M and readiness issues in the general course of instruction as elements of the major case studies and class exercises. Guest lectures by noted authorities in the field are also utilized. This approach places the subjects into context and allows the students to grasp the complexities and interrelationships of of the various issues instead of viewing the subjects in isolation. The current approach may benefit from examining the material that has been gathered by the case studies and using this material to update and expand the content of the course case studies and exercises used at DSMC.
- U.S. Army Management Engineering Training Activity (USAMETA). USAMETA is a management training, research, and consulting organization within the U.S. Army Materiel Development and Readiness Command (DARCOM) and trains 13,000 DoD students per year in short, concentrated management and engineering courses. The current curriculum of 100 courses includes eight which are designed to satisfy expressed training needs for the

R&M engineering community within DoD. Several other courses contain R&M subject material. These courses are designed for R&M support personnel and managers from other functional areas.

- Army Logistics Management Center (ALMC). ALMC is a DARCOM school whose mission is to conduct training, perform research, formulate doctrine, and provide information and consulting programs for logistics management matters. The ALMC curriculum consists of 71 courses. These courses are designed for journeymen and managers. With the exception of a specialized Army-peculiar reliability-centered maintenance course, the ALMC curriculum includes no R&M courses. However, many courses include blocks of training on R&M. The DARCOM Intern Training Center (ITC) located at Texarkana, Texas, is a component of ALMC. ITC provides R&M training for two one-year DARCOM Intern Training Programs--the Maintainability Engineering Intern Program and the Quality and Reliability Engineering Intern Program. These programs are designed to assist graduate engineers in making the transition into the Army R&M community.
- Navy Acquisition Logistics Management School. The school educates Navy military and civilian personnel on the current acquisition and logistics policies and procedures. Each one-week class consists of 15-40 program management,

fiscal and support personnel. One session is devoted to R&M and includes an overview of this R&M study.

- Air Force Institute of Technology (AFIT), School of Systems and Logistics. AFIT conducts courses that are designed to provide instruction in systems logistics and management areas related to military and civilian duty assignments. The Professional Continuing Education (PCE) Program consists of approximately 58 courses of relatively short duration--1 to 7 weeks. Course content generally emphasizes the operational areas of systems acquisition and logistics management. As a part of the above curriculum, AFIT offers four R&M courses for Air Force students. The courses address reliability, R&M research and applications, reliability theory, and life-cycle management.
- Other Short Courses. Other means also used by the military services for R&M training are contract training and utilization of in-house experts. The Defense Logistics Agency (DLA) and the Navy make extensive use of this approach. Such courses are usually intended to be conducted for some limited time period and/or specialized audiences.

c. Action. DoD R&M training is currently being provided by a variety of sources, both in-house and contractor. However, there is no organized program to establish and maintain a coordinated R&M curriculum for engineers, support personnel, or managers on a DoD-wide basis. As a result, there is opportunity for non-uniformity in training, overlap in course offerings, and omissions where training may be badly needed. There is a need to integrate R&M training activities throughout DoD.

Two basic alternatives could meet the criteria specified above:

- Establish a new organization with a mission to provide R&M training and related advice and assistance to the DoD community.
- Assign executive-agency responsibility to an existing organization for R&M training. The executive agent could work closely with DoD, academia, and industry training institutions to develop a comprehensive R&M training curriculum.

In addition, consideration should be given to reestablishing Master's Degree Programs in Reliability at schools like the Army's Red River and the Air Force's Master's Degree School, which were the source of valuable, well-trained people.

#### D. OTHER OBSERVATIONS

##### 1. The Discipline and Structure of Management

a. Observations: The techniques of establishing requirements and structuring them to achieve the desired fielded capability are still not well-understood by management even though they may be understood by the R&M practitioners. Efforts reviewed in this study often resulted in ill-defined requirements, or requirements for unrealistic performance levels.

The net results have been requirements written with good intentions but lacking in their ability to provide a realistic framework for design, development and production. As a result, priorities were not stabilized within the large development efforts necessary to produce systems with fielded performance that met the original expectations. The simple fact that requirements are most often written in contractual terms which are structured so that their achievement will result in field reliability considerably lower than desired continues to escape many involved in acquisition and program management.

The need to improve the nature of the requirements statement and its translation into contractual terms and thence into design is highlighted by the complexity of modern systems and the resultant drive toward more automation in the diagnostics area. Within the built-in-test discipline, specified requirements of 98 percent fault detection have ended up, in some cases, in addressing only one-tenth of the actual malfunctions that the system ultimately experienced (see Fig. 18).

b. Findings: It is essential that more attention be focused on the establishment of realistic requirements, awareness of the program implications to achieve these and incentives for achievement. Program manager and chief engineer personnel, as well as

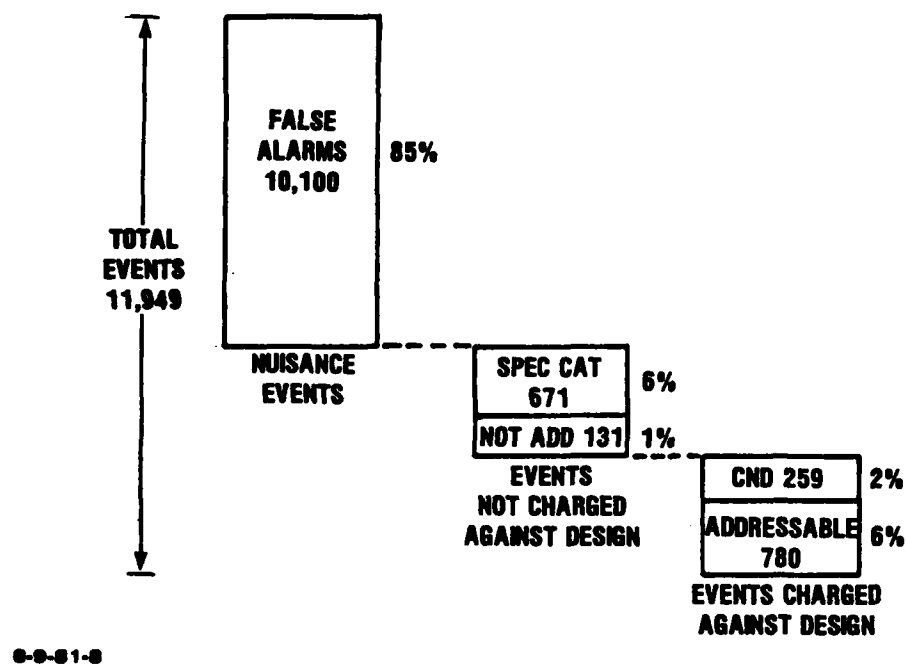


FIGURE 18. Total Diagnostic Events for Complex Electronic Systems



design, reliability and maintainability engineers, must understand the consequences of their respective programmatic actions.

Within the case study review process two discrete high-payoff items were identified: establishment of requirements and the use of contractor incentives.

(1) Establishment of Requirements. Acquisition programs must be structured early starting with concept approval and leading to a Full-Scale Development contract containing realistic R&M requirements (not merely goals), so that R&M can compete effectively for management support with all other program requirements. When R&M requirements are specified as goals, technical performance requirements will receive a higher priority in the management decision process. The FIREFINDER case study provides a good example of goals versus requirements. The TPQ-37 Advanced Development Contract contained only a 250-hour MTBF goal and it appears that the contractor placed a major emphasis on performance (Ref. FIREFINDER Case Study, p. 57/1-23). When the TPQ-37 system went from Advanced Development to Low-Rate Initial Production (LRIP), a firm 90-hour MTBF requirement was added to the contract, along with an incentivized reliability demonstration test. The measured MTBF went from 33 hours for Advanced Development configuration to 115 hours for the LRIP radars. Many things contributed to the reliability improvement; however, it is believed that the management emphasis placed on meeting the reliability requirements during the incentivized demonstration test was a major factor. The R&M requirements must have contract specified verification to be true requirements. The contract must specify the items to be measured, method of measurement and the environment in which the measurement will be made. The planned R&M growth should be a contractual requirement also.

Requirements must be specified within the context of realistic operating environments. Establishment of a mission and life profile for the system early in the program is a necessary precursor to meeting the desired levels for R&M in the field.

Mission profile development should begin in the conceptual phase and continue throughout the program. Detailed design analysis and decisions must be performed in the context of the expected system environmental conditions. If mission profile or life profiles are incomplete, then critical design decisions may not consider the expected operational stresses. Reliability and maintainability are direct functions of these operational stresses.

Detailed design actions must address the stresses that are projected for the total system life profile. The non-mission portion of the life profile of the system will often be a primary design requirement as in the case of missile storage for extended periods (see Fig. 19). The unique aspects of the non-mission portions of the life profile need to be translated into design requirements. Profiles must address the total usage including dormant time, time waiting for the mission, and maintenance time.

(2) Use of Incentives. Contract incentives such as reliability improvement warranties (RIW) can increase contractor motivation to improve reliability and/or maintainability. Figure 20 shows the reliability improvement for the Lightweight Doppler Navigation System (LDNS) observed in that RIW case study. The case studies, even though limited, indicated that use of these incentives could provide payoff through additional contractor actions for reliability growth and diagnostic maturation programs. Other studies have also confirmed this fact. Figure 21 is a summary of data from the Air Force Affordable Acquisition Approach (A<sup>3</sup>). The effect of the period of performance used for assessment must be considered. Short duration measurement periods may have only short-term effects and tend to focus too much attention on the measurement methods rather than on the

- Non-Mission Stresses

Result from:

- Transportation
- Handling
- Storage
- Test or Checkout

- Duration of Non-Mission Periods:

	<u>LIFE</u>	<u>MISSION TIME</u>	<u>PERCENT OF LIFE IN NON-MISSION TIME</u>
Missile Electronics	10-15 yrs	30 min	99.9%
Aircraft Electronics	15 yrs	4,000 hr	96.9%

FIGURE 19. Non-Mission Portions of a System Life Profile are Significant in Stress Levels and Duration

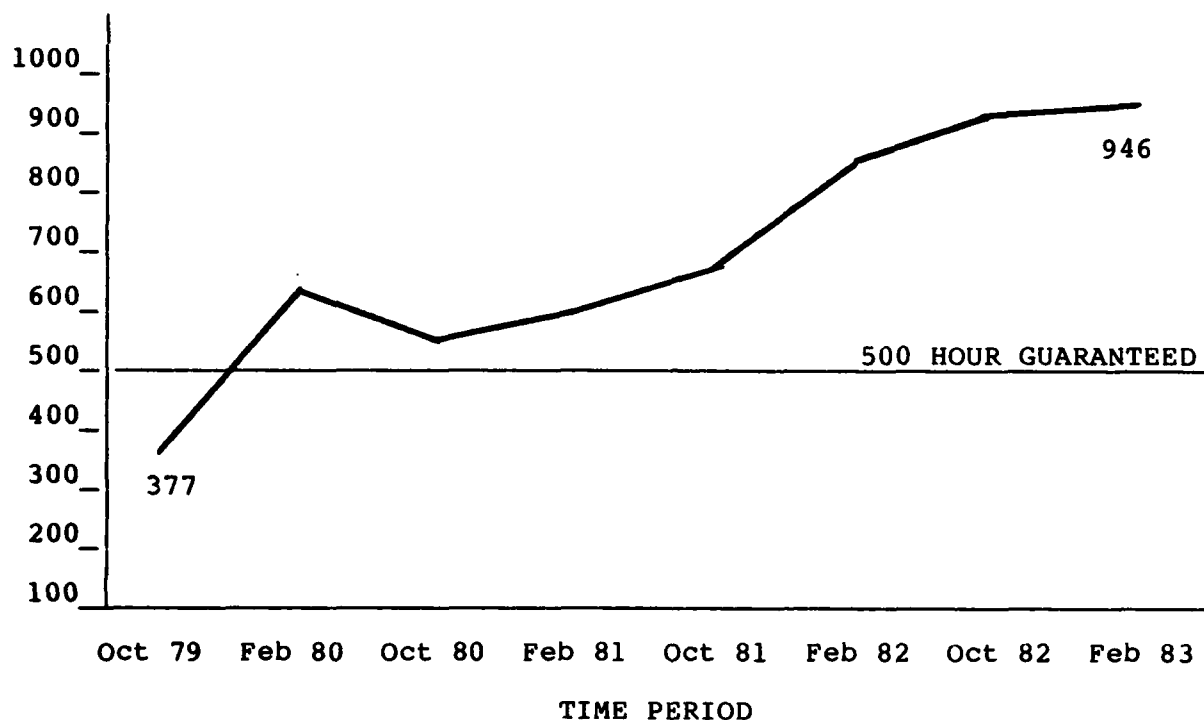


FIGURE 20. Lightweight Doppler Navigation System  
AN/ASN 128 RIW--MTBF Achieved (CUM)

- 10 PROGRAMS WITH RELIABILITY INCENTIVES REVIEWED
- TYPES OF INCENTIVES
  - RIW
  - MTBF GUARANTEE
  - AWARD FEE
  - RELIABILITY PERFORMANCE INCENTIVES
- 9 OUT OF 10 FIELDIED SYSTEMS MET OR EXCEEDED  
RELIABILITY REQUIREMENTS
- 8 OF 10 SYSTEMS HAD INCENTIVES BASED ON  
OPERATIONAL PERFORMANCE

---

WHAT WAS DONE DIFFERENTLY

- |                                  |          |
|----------------------------------|----------|
| ● INCREASED MANAGEMENT ATTENTION | 10 OF 10 |
| ● RELIABILITY ACHIEVEMENT        | 3 OF 10  |
| PROGRAM MANAGER ASSIGNED         |          |
| ● INCREASED DESIGN ANALYSIS      | 4 OF 10  |
| ● ADDITIONAL TRADE STUDIES       | 4 OF 10  |
| ● MADE DESIGN CHANGES            | 4 OF 10  |
| ● ADDITIONAL TESTING             | 5 OF 10  |

FIGURE 21. R&M Contract Incentive

actions required to improve the long run operational R&M performance of the equipment. For example, an award fee for passing a reliability qualification test provides an incentive until the test is passed, but it will not provide an incentive for the subsequent production of reliable or maintainable systems. Other contractual levers need to be employed for the production phase. An RIW may be structured to provide incentives for the contractor to design and test, to mature the operational system (R&M), and to maintain quality in production because it is also in his best interest to do so. Up-front design actions taken in response to an RIW will, however, be related to the contractors' prediction of reliability risk and the economics of making or not making the objective. An efficient RIW may be difficult to negotiate for a sole source contract. RIW's appear most suitable for systems for which depot repair is economical and where risks are bounded.

It should be noted that the techniques available to provide incentives to contractors, e.g., awards fees, RIWs, etc., will not by themselves assure success. A well-thought-out and coordinated set of incentives, requirements, program structure, test program, and maturation are all needed. The cases studied clearly showed that R&M incentives, even small ones, have impacts and that well-structured R&M incentives have significant potential.

Incentive programs can be structured to promote both disciplined R&M design and development, to bridge the gap between lab results and field usage, and to aid in the rapid correction of field identified problems. Incentives should be tailored to individual programs, not merely copied blindly from program to program. Experience with incentives should be analyzed in context and the results of these analyses used to educate appropriate DoD management to assure that programming and budgeting activities include provisions for incentives.

## 2. New Starts or Upgrades

a. Observations: If defense policies are successful and major hostilities are avoided during the next two decades, a high percentage of the Year-2000 inventory of equipment is already in the field today (see Fig. 22). The DoD Acquisition Guidelines established PrePlanned Product Improvement (P<sup>3</sup>I) as the second of 31 priorities. This in essence was a proposal to keep the fielded inventory from becoming a "wasting asset" by structuring the system design process to accommodate a strategy of upgrade both to improve performance and reduce failures.

	<u>1990</u>	<u>2000</u>
AIRLIFT ONLY	99%	83%
ALL:	93%	55%
BOMBERS		
TANKERS		
STRATEGIC DEFENSE		
AIRLIFT		
TACTICAL FIGHTERS		
SOURCE: AF/XOXF		

FIGURE 22. Percentage of Current Air Force Aircraft Expected to Still be in Service in 1990 and 2000

b. Findings: One of the new challenges proposed by a disciplined approach to program structuring is recognition of the fact that in spite of the best design and manufacturing efforts there still remain significant unknowns which can only

be detected and addressed after the system is operated in the field by the actual user command. Recognition of this is imperative to provide structuring for total growth and maturation from early program conception through the first two or three years of fielding experience. This total growth concept must be closely coupled with the disciplined approach discussed in Appendix B to prevent it from degenerating into a practice of to deferring today's problems until tomorrow.



APPENDIX A

CASE STUDIES ORGANIZATION AND PARTICIPANTS

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A-1

## APPENDIX A

### CASE STUDIES ORGANIZATION AND PARTICIPANTS

This appendix describes the organization established to treat the program structure aspects of the study objective. In addition, the case study methodology, selection process, and program review process are discussed and the major participants identified.

#### A. OBJECTIVE

The overall study objective stated in the Task Order is:

"To identify and provide support for high-payoff actions which the DoD can take to improve the military system design, development and support process so as to provide quantum improvements in R&M and readiness through innovative uses of advancing technology and program structure."

From this objective, two distinct program structure-related tasks were derived:

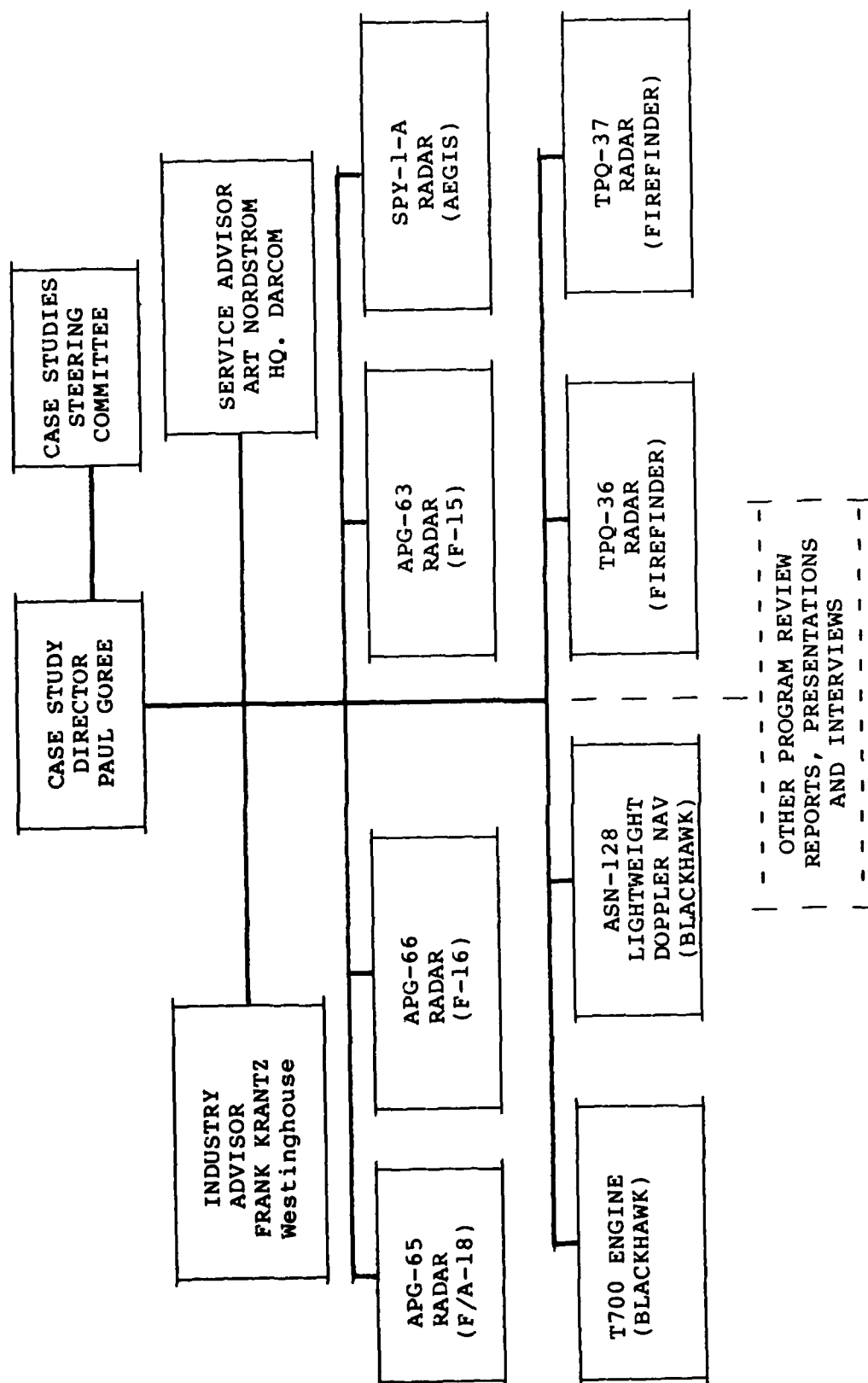
- (1) To assess the impact of program structuring on future DoD requirements for improved R&M and readiness; and
- (2) To evaluate the potential and recommend strategies that might result in quantum increases in R&M or readiness through innovative use of program structuring.

## B. CASE STUDY STRUCTURING

In structuring this portion of the overall study activity, consideration was given to the methodology to be employed, the selection of cases and the overall review process to be used. This structuring was established by the study executive council in the early phase of the study and a detailed case study organization was instituted, as shown in Figure A-1. Case study results are contained in IDA record documents (Refs. A-1 through A-6).

Consideration was given to breadth and depth of case study activity. Goals were established to: look across all Services (Army, Navy, and Air Force); encompass different sizes (small to very large); look at a range of complexities (relatively simple to very complex) and; look at various operational environments (truck-mounted, helicopter, fighter aircraft and shipboard).

In establishing the early approach, the executive council decided that the activity should be focused on successful systems in an attempt to glean the strengths of each into an overall composite structure which might be implemented in the next generation weapon system. By taking this approach and establishing open and candid exchanges, it was felt that people close to the program might be more inclined to discuss failures as well as successes, once they recognized that this study was not geared to "rock throwing" or "witch hunting." This turned out to be a successful approach as many avenues were opened on many programs.



**FIGURE A-1. Case Study Organization**

### C. METHODOLOGY

In developing the methodology to permit cross-program analysis, data were collected from the F-16, Blackhawk and F/A-18 programs to get an idea of areas upon which to focus the case study activity. The top ten contributors to maintenance events were as follows:

<u>RANKING</u>	<u>F-16</u>	<u>TOTAL MAINTENANCE EVENTS</u>
	<u>ITEM</u>	
1	Engine	14.9%
2	Fire Control Radar	12.5
3	Airframe	12.4
4	Landing Gear	7.4
5	Auxiliary Power	6.7
6	Fuel System	6.2
7	Flight Controls	5.8
8	Crew Station	4.1
9	Electrical Power	3.7
10	Lighting	<u>3.0</u>
		76.0%

<u>RANKING</u>	<u>UH-60A BLACKHAWK</u>	<u>TOTAL MAINTENANCE EVENTS</u>
	<u>ITEM</u>	
1	Airframe	19.5%
2	Rotor Systems	16.4
3	Avionics	10.9
4	Drive System	9.2
5	Flight Control System	8.2
6	Electrical System	5.7
7	Instrument System	5.6
8	Landing Gear System	5.1
9	Pneudraulics	4.5
10	T700 Engine	<u>4.2</u>
		89.3%

<u>F/A-18</u>		
<u>RANKING</u>	<u>ITEM</u>	<u>TOTAL MAINTENANCE EVENTS</u>
1	Weapons Control	18.7%
2	Landing Gear	10.7
3	Airframe	9.0
4	Electrical	5.8
5	Fuel System	5.8
6	Weapons Delivery	5.5
7	Flight Controls	5.1
8	FCES	4.3
9	Maintenance and BIT System	4.2
10	Environmental Control System	<u>3.6</u>
		72.7%

From the review of the "Top 10" lists, the focus centered on radars and engines, with high interest in fire control radars due to potential implications of the associated built-in-test/diagnostics. In addition, it was felt that some findings in the radar area could be translated credibly to complex electronics in general.

The "Top 10" lists pointed to another area of interest as well. Note that the F-16 engine is number one on its list while the Blackhawk engine drops to number ten. In an effort to identify what was done to achieve major improvements in engine development and to move into the mechanical systems area, the T700 engine was added to the list of studies.

#### D. SELECTION PROCESS

The process of selecting systems for case studies evolved over the course of several months. Nominations for candidate systems were accepted from both the Services and industry, representing many diverse capabilities. The candidates ranged from the relatively simple AIM-7 and AIM-9 missiles to the very complex TRIDENT submarine. Between these extremes were engines, radars and navigation systems representing varying degrees of complexity.

After considerable discussions within the core group, a decision was made to do pilot case studies on the airborne radars currently installed in the F-15, F-16 and F/A-18 aircraft. The intentions were to develop a case-study model using similar airborne radar systems that could then be used to perform studies on a relatively large number of other systems. The airborne radar systems seemed to be ideal choices for the pilot programs because they were high on the list of subsystems that usually cause major problems for weapon systems in each Service.

Initial efforts to develop case studies from researching data and literature sources yielded poor results at best and dictated a change in tactics.

The second effort to bring together a useful case study resulted in the formation of working groups composed of prime contractors and subcontractors and Service program office representatives. Bringing together the key people associated with the programs significantly improved efforts to capture what was done to make each program successful.

In conducting the initial case studies it became apparent that capturing data in a format conducive to comparing programs would be difficult even with like systems because of differences in the way data are preserved on various programs and the manner in which various programs are managed. This fact, coupled with an understanding of the amount of time and effort required to

do comprehensive case studies, helped focus for the remaining case-study activity. As a result, the scope was narrowed to look at radar systems of varying complexity (Lightweight Doppler Navigation System, Airborne Fire Control Radars, Weapon Locating Radars, and Shipborne Fire Control Radar), and one mechanical system, the T700 engine. The inclusion of the T700 was important for two reasons. First, it added a mechanical system to the list and second, it provides a bridge to follow-on efforts that might include additional mechanical devices.

#### E. PROGRAM REVIEW PROCESS

R&M Program Review Elements were established early in the study program so that case studies could be conducted in a consistent and thorough manner. These elements provided a structure for gathering information for the case-study reports. The 26 review elements were under five major headings: contracting, management, design, manufacturing and test and evaluation. Each element was defined and a list of questions to be addressed was prepared.

Library research provided a substantial number of reports, symposium papers, military standards, and other information pertinent to the study (over eight-hundred and fifty documents; Ref. IDA Record Document D-18, "Bibliography").

Prime and subcontractors were visited and information gathered through personal interviews with people directly involved with the program. In some cases, the contractor did the bulk of the case-study report work; in others, the contractor provided basic inputs and the IDA R&M study group personnel assisted in the preparation of the report. Data from the individual case study reports used in this report were reviewed for accuracy with the contractors and the military services. Contractor personnel, involved in the preparation of case studies, participated in the IDA R&M Study



Group Meetings accompanied by representatives from the appropriate military procuring activity.

The case study review approach was based on building a foundation for analysis and to analyze the front-end process of successful programs for ways to attain R&M, mature it, and improve it. Concurrency and resource implications were considered. Existing case study reports, new case studies conducted specifically to document quantitative data for cross-program analysis, and documents, presentations, and other available literature were used to build the analytical foundation. In addition, focused studies for specific technology implications were conducted by individual technology working groups and documented in their respective reports.

In some areas where program documentation and records did not exist, the actual experience and judgment of those involved in the programs were captured in the case studies. Likewise, in the analysis process, the broad base of experience and judgment of the military/industry executive council members and other participants was vital to understanding and analyzing areas where specific detailed data were lacking.

#### F. CASE STUDY PARTICIPANTS

Without the detailed efforts, energies, patience and candidness of those intimately involved in the programs studied, this effort would not have been possible within the time and resources available. Participants making major contributions to these case studies are listed below. In addition to the listed participants, candid comments and inputs were received from personnel from many other programs, from generals, admirals, and other senior executive Service personnel throughout the course of the study. Every effort has been made to capture these valuable lessons within the text of this document.

# CASE STUDY PARTICIPANTS

Bailey, E.W.	McDonnell Douglas
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General Electric Co.  
McDonnell Douglas  
McDonnell Douglas  
General Dynamics  
McDonnell Douglas  
Hughes Aircraft Co.  
General Electric Co.  
HQ AFALD/PTR

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- A-1. Institute for Defense Analyses, "F-15 AN/APG-63 Radar Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-19, August 1983.
- A-2. Institute for Defense Analyses, "F/A-18 AN/APG-65 Radar Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-20, August 1983.
- A-3. Institute for Defense Analyses, "F-16 AN/APG-66 Radar Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-21, August 1983.
- A-4. Institute for Defense Analyses, "T700 Engine Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-22, August 1983.
- A-5. Institute for Defense Analyses, "AN/APG-128 Lightweight Doppler Navigation System Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-23, August 1983.
- A-6. Institute for Defense Analyses, "AN/TPQ-36 and AN/TPQ-37 FIREFINDER Radar Case Study Report (IDA/OSD R&M Study)," IDA Record Document D-24, August 1983.

APPENDIX B

A DISCIPLINE FOR PLANNING AND  
ANALYZING PROGRAM STRUCTURE

## APPENDIX B

### A DISCIPLINE FOR PLANNING AND ANALYZING PROGRAM STRUCTURE

In the course of conducting case studies for this project, an organized approach for analyzing weapon system program structure has been developed and tested over the duration of the project. Though initially structured to permit evaluation and insight into existing programs, perhaps the more important contribution could come from using this approach for planning and analysis during the formative stages of the creation of weapons systems programs, as well as a monitoring tool for management use throughout the life of the program.

The focus of this process is to understand reliability, maintainability and readiness implications of programmatic structuring and management decisions. It is based on actual experiences which are documented in detail in Appendixes C and D, the individual case studies and expert judgment of the many military and industry study participants. It encompasses considerations for variations in programs and the acquisition environment; structuring for R&M in weapon system programs; interrelationships and dependencies of program elements; and concurrency and scheduling.

This disciplined approach, if followed, could lead to significant improvements in R&M through innovative program structuring. These improvements would be the result of a better understanding of overall considerations necessary for improved R&M and the associated risk of management decisions. In addition, this section provides guidelines that any program manager or chief engineer can build on to improve their own abilities for improved design and management.

## A. VARIATIONS IN PROGRAMS AND THE ACQUISITION ENVIRONMENT

Variation in programs and variations in the acquisition environment were considered in reviewing programs. Difference in the types of systems, the expected operational environment and usage, the technology aspects of the system as well as the acquisition environment existing at the time, played major roles in associated program structuring.

### 1. Variations in Programs

An analysis across the F-15 (APG-63), F-16 (APG-66) the F/A-18 (APG-65), T700 and other case studies as well as other program reports shows that the methods used by the Services to structure programs must consider: what type of system is being procured, what operational environment and usage is intended, and what technology applications might be used. To structure programs, review and/or analyze programs and manage programs, careful consideration must be given to these areas as there is no single rule of thumb which addresses all concerns in structuring programs for R&M.

a. Type of System. R&M elements needed in programs are dependent on and should be tailored to the type of system. Considerations for mechanical systems such as engines might be similar to electronic systems in some areas and grossly different in others. Requirements for a "thermal analysis," for example, would be a similar program element for both engines and radars. A requirement for "derating criteria," which is important in electronics parts, would have little meaning to an engine contractor but "margin of safety" or allowable strengths of material would have considerable meaning. Similarly, other considerations may come into play in other technical areas such as electrooptical. The structuring presented in this volume was derived from reviews

of high-performance radars, and, while it might be representative of a class of complex electronics, it does not necessarily accommodate all types of systems, although some similarities may exist.

b. Operational Environment. The installation and usage of hardware dramatically influences the resulting reliability of the hardware. As an example, the Magnavox ARC-164 UHF Radio, widely used in the Air Force inventory, has dramatically different removal experience depending on the aircraft installation involved, as shown in Fig. B-1.

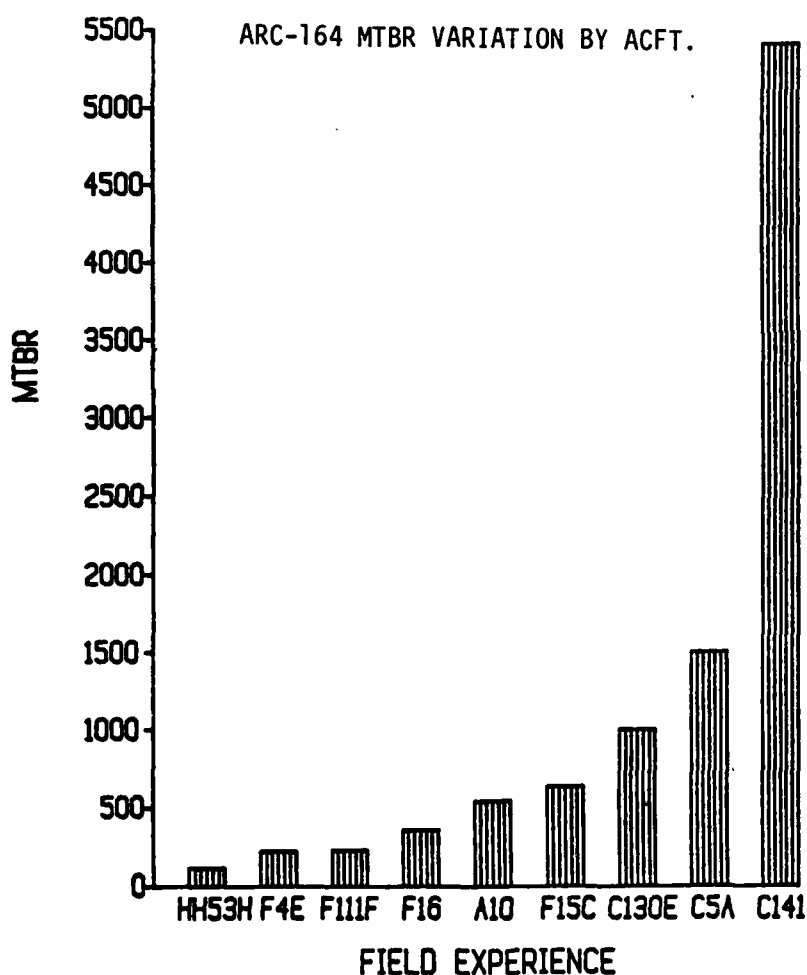


FIGURE B-1. Impact of Installed-Use Environment  
(Magnavox ARC-164 UHF Radio, AFM 66-1 Data, Jan-Dec 1982)



Another example (Fig. B-2) is the ARN-118 TACAN.

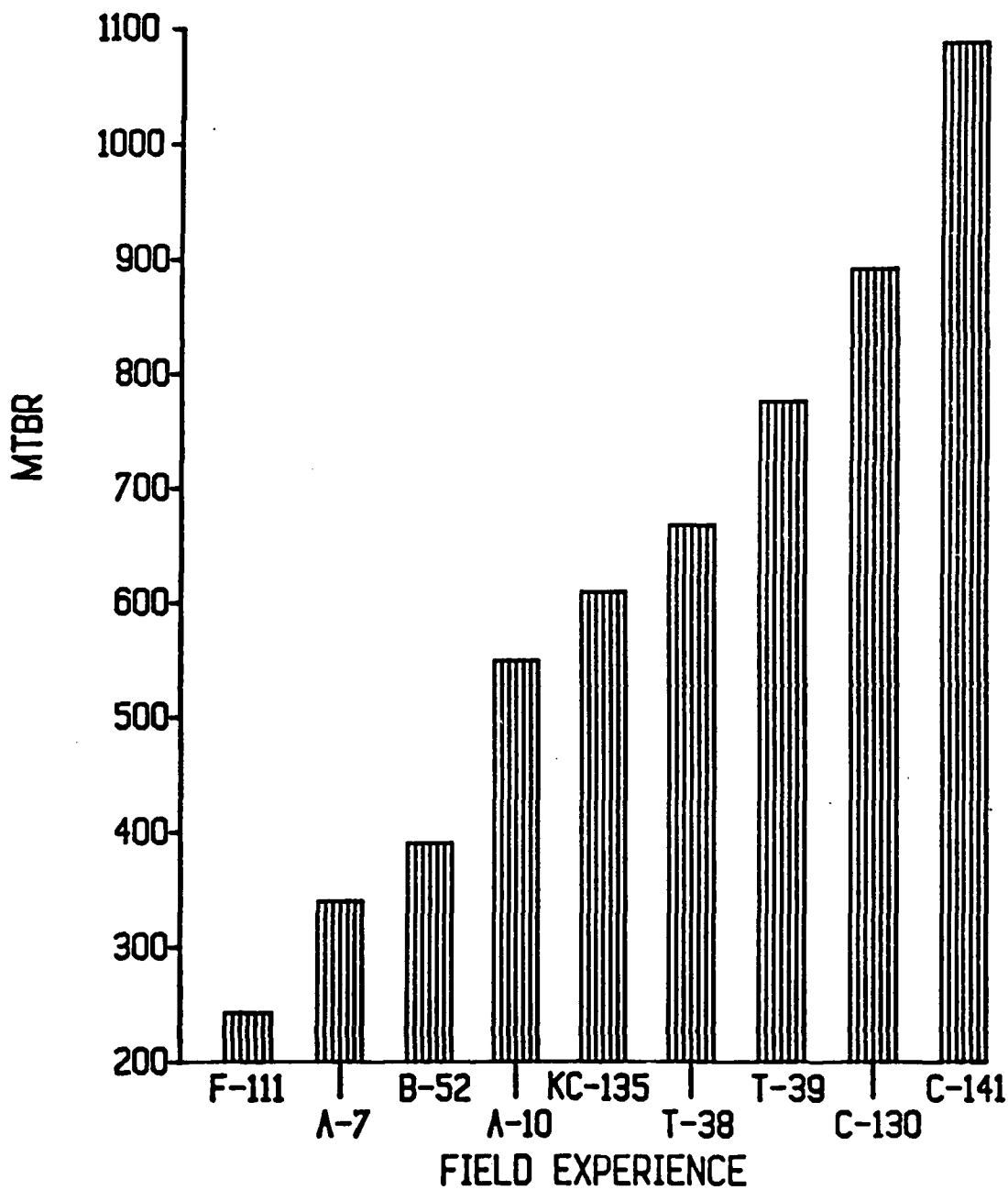


FIGURE B-2. Removal Experience Versus Aircraft  
(ARN-118 TACAN, AFM 66-1 Data, Jan-Dec 1978)

The UHF radio and TACAN experience points out that there is inherent uncertainty in attempting to translate field occurrences to design features/attributes of one program for use in planning another program without first attempting to understand the many subtle, but potentially major, impactors.

As another example, in the case of the F-15 design, the 20mm Gatling-type gun (M61-A1) is located on the right side of the airplane adjacent to the wing root, above, outboard, and aft of the right engine air inlet plane. Because of the remote location of the gun, the radar peak "g" level is only 5 g's compared to 24 g's for the F-4E (APQ-120) radar which has the gun in the nose. For the F-16, the gun is located on the left side of the airplane in the wing root (strake) area, aft and above the engine air inlet so that it too has a minimum effect on the radar. On the F/A-18, the gun is located in the nose above the radar. Understanding the potentially adverse effects of this configuration allowed the effects to be minimized by providing sealing from the gun gas and vibration isolators at the radar interface between the rack and aircraft bulkhead.

Similarly, there are major variations which might occur when going between different relative military user environments (e.g., Navy--salt and sea; Army--mud and sand) and resource environments (e.g., skills, facilities, etc.). Thus, in reviewing or planning programs, R&M elements, schedules and resources must consider these types of factors.

c. Technology Applied. The evolutionary stage of the hardware/software involved and the degree of the state-of-the-art design in a system play a major role in attempting to structure R&M elements into a program. While a fifth-generation system of an evolutionary technology might effectively incorporate changes to improve R&M as a result of test and field experience, a brand new first-generation state-of-the-art system would in all

probability require special considerations which are sufficiently flexible to fit within the design, test-analyze-and-fix processes associated with meeting functional performance requirements with the new design technology.

In the case of the radars studied, the basic radars were developed through an evolutionary process; evolution of the F-15 Radar, after original design, is shown in Fig. B-3.

A number of electronic technologies became available in the late 1960s that allowed the formulation of a radar system that provided detection and tracking over all aspects of look-down in ground clutter. This radar, the APG-63, is a high-power, coherent pulse doppler system that combined the proven long-range head-on and look-down detection capability of a high PRF system with a new Airborne Moving Target Indication (AMTI) waveform in the medium PRF region for shorter-range, all-aspect look-down capability necessary for air combat tactics. The design flexibility of diverse waveforms, high and medium PRFs, were made available through the development of the shadow grid traveling wave tube transmitters. The low antenna sidelobe levels that are critical to the new medium PRF AMTI mechanization were made possible by precise control of planar array radiation distributions, another new technology development.

The development of all solid-state digital signal processing was the most significant reliability-related event in the APG-63 radar evolution, literally revolutionizing radar design concepts by allowing a mechanization which shifted hardware functions to software functions and thus greatly improving the reliability. A newly-developed digital multiplex bus simplified the radar interface with other avionics systems and provided the communication link necessary for on-board, Built-In-Test (BIT) and System Test (ST), thus improving both reliability and maintainability (diagnostic). The continuing progress in digital technology has allowed the radar to grow both in performance and reliability.

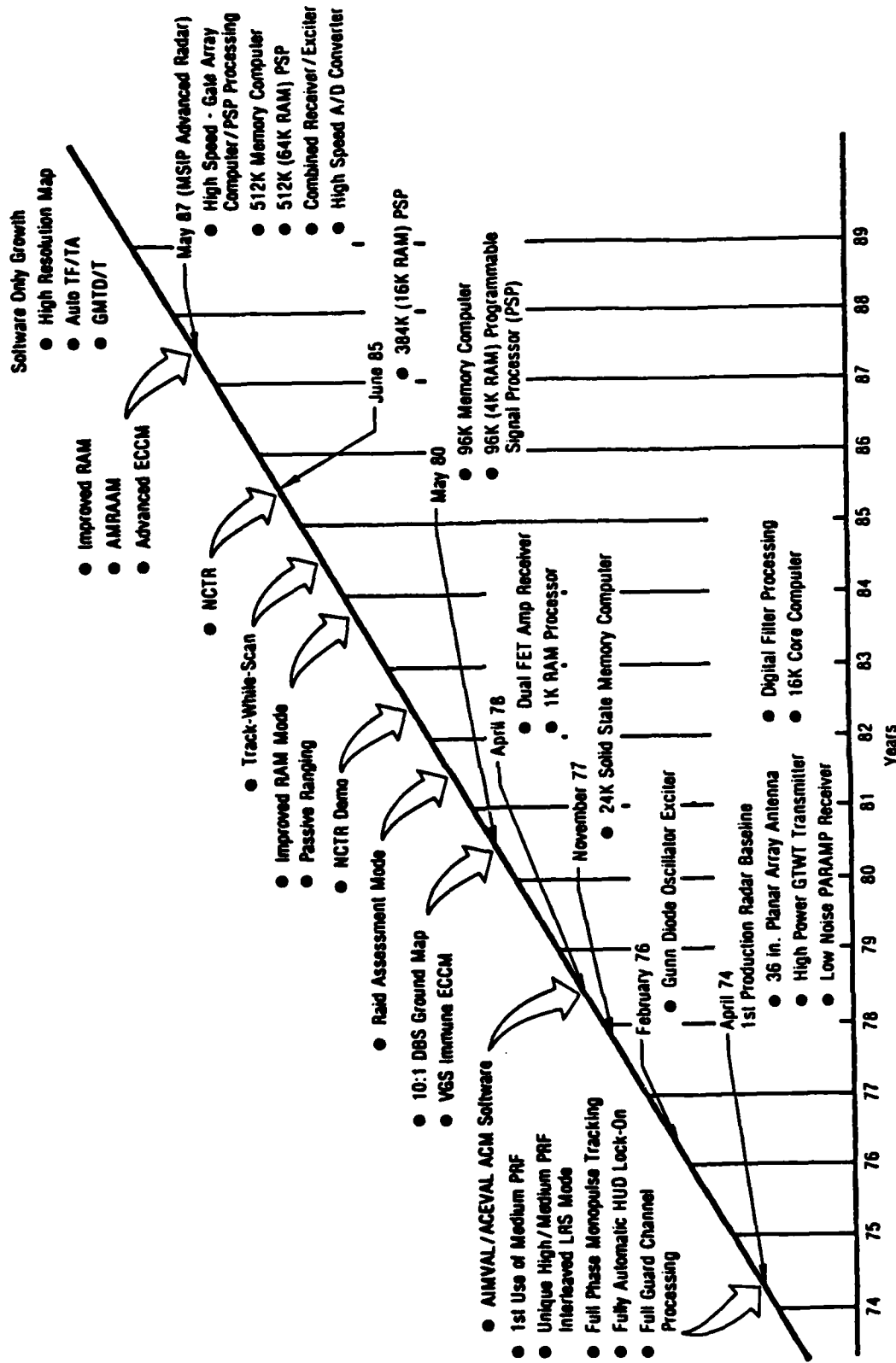


FIGURE B-3. F-15 Radar System Evolution

A Programmable Signal Processor (PSP) was introduced into the APG-63 in 1980, and, besides changing previously hard-wired digital processing functions to software, it provided higher reliability through the use of higher density 4K BIT RAM devices.

A 16K-word ferrite-core memory general-purpose digital computer was initially used in the APG-63 to provide automatic control of all radar modes. This included all Built-In-Test routines and BIT test result storage in a coded matrix that is made available for playback for the maintenance crew. A breakthrough in solid-state Electrically Alterable Read-Only Memory (EAROM) devices allowed the introduction of a 24K-word Solid-State Memory Computer in 1977 as a value change program cost savings. This computer had the growth capability to 96K-word (or  $96K \times 24 \text{ Bit} = 2.3 \text{ Megabit}$ ) capacity by module addition. A portion of this was used to extend the Built-In-Test capability. In 1980, the increased storage was used in conjunction with the PSP, which resulted in improved fault detection/isolation in some LRUs.

The continuous application of later technology has allowed the radar to achieve reliability and maintainability growth and to reach the present part count of 18,800, down some 4,000 parts from the complexity which existed for the R&D program. Improved F-15 C/D radar R&M is evident in the AFM 66-1 reports compared to the earlier F-15 A/B radar experience. This is largely attributed to the May 1980 introduction of the Programmable Signal Processor and the improved solid-state digital memory computer (Ref. F-15 Case Study, pp. IB-2,-3).

Similarly, the F-16 Radar was the result of design evolution as shown in Fig. B-4. This evolution led to the development of the modular APG-66 radar used on the F-16. Westinghouse began design and development activity in 1971 for a new series of modular radars. The WX series of radars--and in particular the WX-200--used the pulse doppler principle and advanced digital

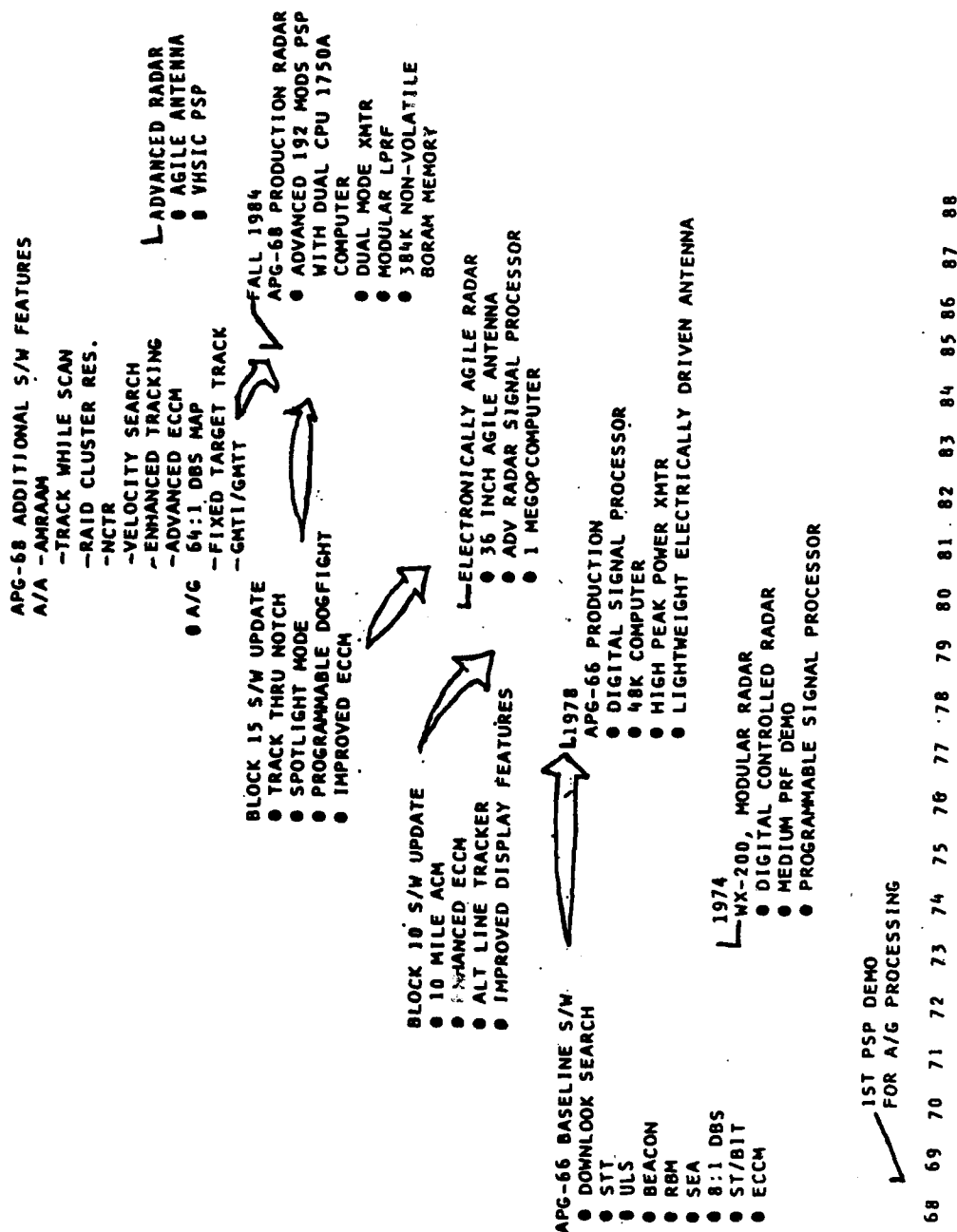


FIGURE B-4. F-16 Radar System Evolution

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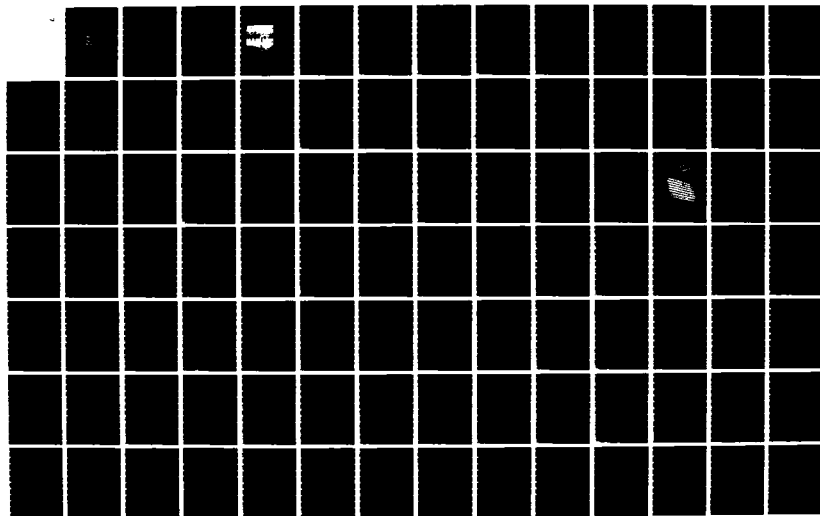
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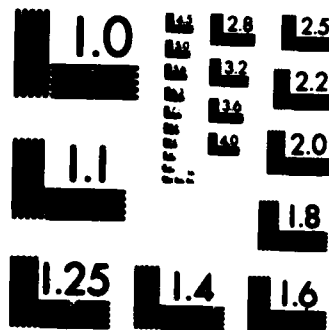
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techniques. Demonstration of these balanced design techniques led directly to the subsequent balanced design and development of the APG-66 in July 1974 (Ref. F-16 Case Study, pp. IB-12).

The F/A-18's APG-65 radar draws on all of the APG-63 experience and contains a completely programmable signal processor that is similar to the one used on the F-15 C/D radar and has at least one-third of the circuit boards that are common. Figure B-5 depicts the system evolution.

The F/A-18 APG-65 radar contains more computer memory than any other current production fighter. This is due, in part, to the numerous radar modes and to the large storage requirements of the multi-mode programmable signal processor (Ref. F/A-18 Case Study, p. 25). The following summarizes current memory capabilities of the three airborne radars studied:

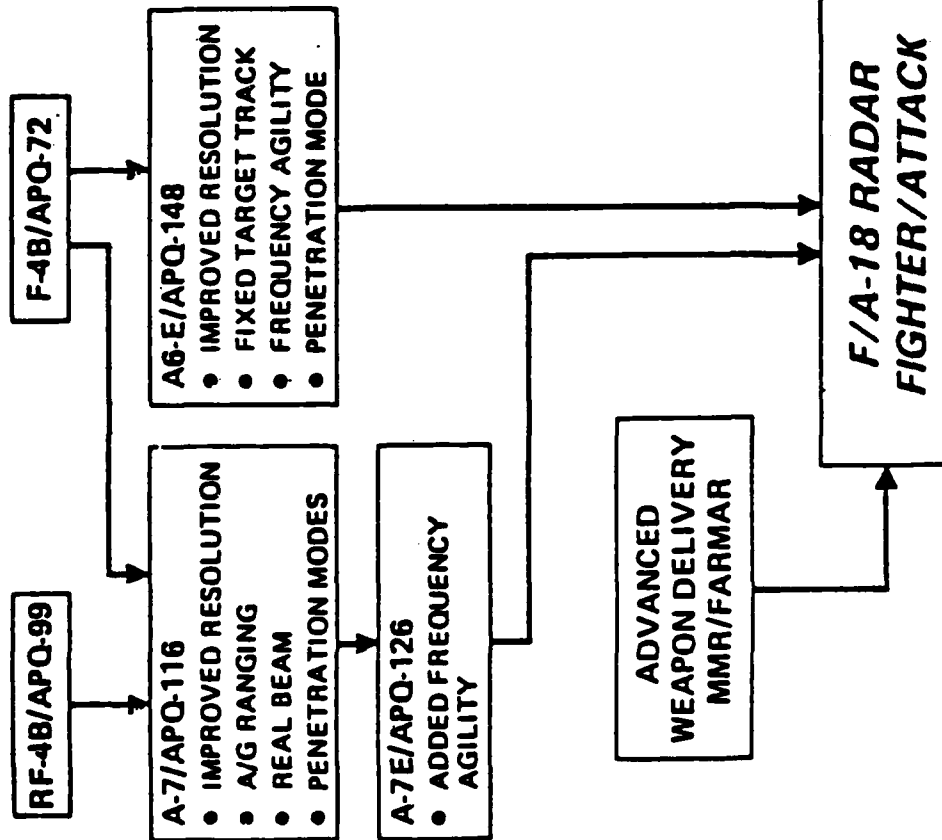
F-15	96K	24-Bit words
F-16	48K	16-Bit words
F/A-18*	210K	16-Bit words.

In addition to the basic evolution of hardware systems, the introduction of new component technologies has impacted overall R&M and associated program elements and structures. Figure B-6 shows the relative influences of technology introduction in the form of the vacuum tubes and the subsequent transition to solid-state components and then integrated circuits/microcircuits.

For early vintage, predominantly vacuum tube radars such as the MG-13 (F-101B) and the APQ-72 (F-4B), average part failure rates on the order of 35 in 1,000,000 hours are shown as derived from field reliability data. With the technology shift toward solid-state (transistors and diodes) as incorporated in the APQ-120 (F-4E), parts failure rates improved to an average part failure rate on the order of 10 in 1,000,000 hours, as shown. Now, with modern radar systems such as the APG-66 (F-16A), APG-63

\*Includes 30K 16 BIT words dedicated to fault detection and isolation (Note: F-14 total memory is only 30K).

# ATTACK



# FIGHTER

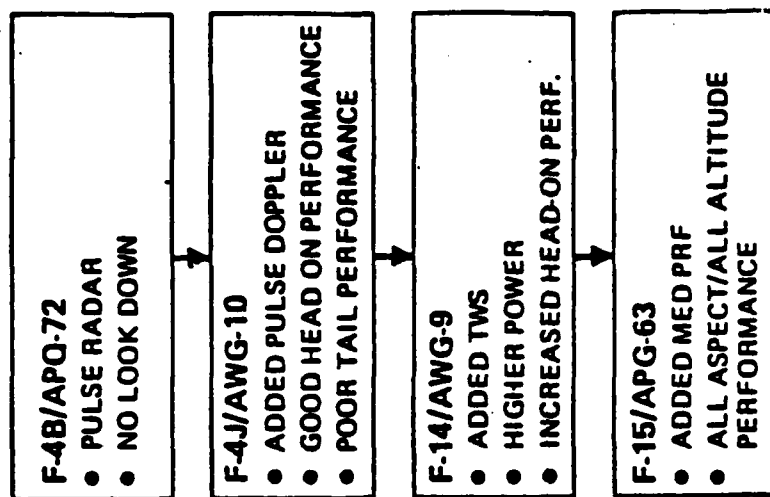


FIGURE B-5. F-18 Radar System Evolution

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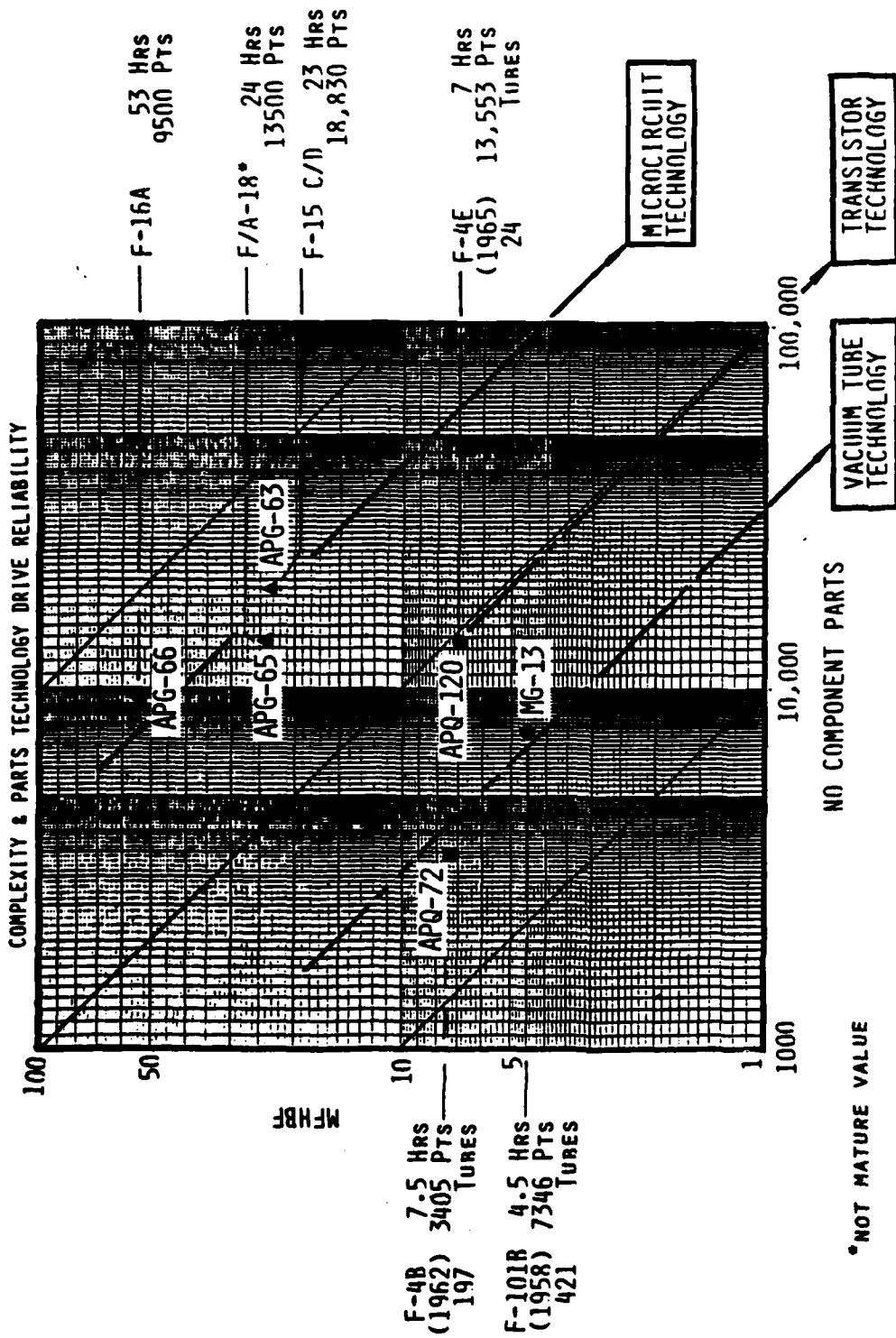


FIGURE B-6. Component Technology Influence on R&M

115/3-12

(F-15 C/D), and the APG-65 (F-18), which utilize integrated circuit/microelectronic devices, the average part failure rate has improved to the order of 2.5 in 1,000,000 hours.

To realize fully the benefits of the inherent improvement in components and the resulting improvement in system reliability, new programmatic elements for R&M had to be evolved with the technology (e.g., the introduction of junction temperature as a new parameter for reliability design consideration for solid-state devices). Similarly, as new and advancing technologies surface in the future, additional elements will surface for consideration in structuring and conducting R&M programs.

The evolutionary process seen in the development of radars can also be illustrated in the T700 engine development. A series of engine component advanced technology programs on compressors, turbines, recuperators, inlet particle separators, etc., were initiated in anticipation of future aircraft requirements. These concurrent component developments evolved into a competitive demonstration program that validated the new engine state-of-the-art technology advancement and reduced the risk of concurrency in the engine and aircraft development. The advanced technology program illustrated in Fig. B-7 was a significant contribution to the high reliability and reduced maintenance workload of the T700 engine.

#### ADVANCED TECHNOLOGY--MODERN ENGINE

- LOW FUEL CONSUMPTION--OPTIMIZED FOR CRUISE
- BUILT FOR THE ENVIRONMENT
  - INTEGRAL SAND SEPARATOR
  - BUILT-IN COMPRESSOR CLEANING
  - RUGGED COMPRESSOR
- SIMPLIFIED PILOT CONTROL
- REDUCED MAINTENANCE WORKLOAD
  - NO ADJUSTMENTS
  - 10 STANDARD TOOLS FOR ALL UNIT AND  
INTERMEDIATE MAINTENANCE
  - HIGH RELIABILITY/LONG LIFE

FIGURE B-7. T700 Engine Characteristics

## 2. Variations in the Acquisition Environment

Many variations exist in the acquisition process. This section provides a discussion of the changing emphasis that the acquisition environment (time) has had on R&M requirements, the changes brought about through new directives and standards, funding characteristics, and the effect of the DoD acquisition policy, i.e., concurrency.

a. A Changing Emphasis for R&M. The acquisition environment for major weapon systems has varied considerably over time with respect to R&M. Generally, considerations for R&M are most apparent during peacetime and tend to diminish during wartime. The APQ-120 radar for the F-4E aircraft is an example of a wartime (Vietnam) development where equipment delivery was the most important consideration and as a result, R&M provisions were deferred until the system was fielded. Prior to 1970, aircraft ground support equipment (GSE) was exempted from R&M consideration in the major system development. As system complexity increased, GSE R&M had to be expanded to preclude more problems with ground equipment than with the aircraft it was to support.

More recently, emphasis on flight simulators highlights new areas for concern. These systems, which generally are more complex and costly than the systems they simulate, have traditionally been developed under R&M programs patterned after the aircraft systems. Today, considering the difference that environment and use place on these systems, relative to the systems they simulate, R&M programs, structured for the unique requirements of simulators, are in order.

b. DoD Directives/MIL Standards. The character of R&M programs has varied over time as new weapon systems have been developed. Requirements for obtaining R&M objectives, as stated

in request for proposals, have reflected the popular notions at the time as well as the then current world situation. Several documents have had a significant effect on weapon system development and are identified here:

- 1957--Advisory Group on Reliability Electronic Equipment (AGREE) Report. Task 3 of the AGREE report set forth sequential testing with the concepts of Specified MTBF ( $\theta_0$ ), Minimum Acceptable MTBF ( $\theta_1$ ), Discrimination Ratio ( $\theta_0/\theta_1$ ) and Decision Risks ( $\alpha, \beta$ ). Sequential testing grew in popularity and began to replace fixed length testing as a requirement in many contracts.
- MIL-STD-785B, 15 SEPTEMBER 1980, RELIABILITY PROGRAM FOR SYSTEMS AND EQUIPMENT DEVELOPMENT AND PRODUCTION. This military standard consists of basic application requirements, specific tailorable reliability program tasks, and an appendix which includes an application matrix and guidance and rationale for task selection. Provisions include:
  - a. Emphasis on reliability engineering tasks and tests.
  - b. A sharp distinction between basic reliability and mission reliability; measures of basic reliability such as Mean-Time-Between-Failure (MTBF) which include all item life units (not just mission time) and all failure within the item (not just mission critical failures of the item itself); and application of basic reliability requirements to all the items.
- MIL-STD-470A, 3 JANUARY 1983, MAINTAINABILITY PROGRAM FOR SYSTEMS AND EQUIPMENT. This Military Standard consists of basic application requirements, specific tailorable maintainability program tasks, and an appendix which includes an application matrix and guidance and rationale for task selection. Provisions include:

- a. Emphasis on the need for including testability considerations as part of the Maintainability Program. Recognition has been given the fact that Built-In-Test (BIT), external test systems and testers critically impact not only the attainment of maintainability design characteristics but acquisition and life-cycle costs as well.
  - b. Emphasis has been placed on considering maintainability program needs at all three levels of maintenance (organizational, intermediate, and depot.)
- 
- MIL-STD-471A, 10 JANUARY 1975, MAINTAINABILITY VERIFICATION/DEMONSTRATION/EVALUATION. This standard defines a planned program for verification, demonstration and evaluation of the achievement of specified maintainability requirements and for the assessment of impact on planned logistic support.
  - 1965--MIL-STD-781A--Reliability Tests: Exponential Distribution. This military standard reflects the concepts of the AGREE report and expands the application to include a "shopping list" of test plans and test levels. A method, which was later dropped in the "B" and subsequent revisions, for determining the number of production test articles based on MTBF, test time, and production rate was included. Plan III and Level F which specified temperature variation from -54°C to +71°C and sine vibration of 2.2 g's peak acceleration at any nonresonant frequency between 20 and 60 cps was typical. Revision C, dated 21 October 1977, is now in effect on newer programs, and replaces the vibration requirement with random vibration and/or swept sine vibration from 20 to 2000 cycles, a more realistic representation of modern jet aircraft vibration environments.



- 1977 NAVMATINST 3000.1A. This instruction formalized a shift in the Navy approach to R&M from numbers/test approach to the design/manufacturing approach that was used successfully at NASA.
- 1980 DoD Directive 5000.40. This directive establishes policies and responsibilities for the reliability and maintainability of systems, subsystems and equipment. The directive set forth the policy of defining fundamentals of design, manufacture and management which would result in delivery of reliable and maintainable hardware systems to the operational forces. It addresses the R&M achievements that shall be accomplished during all phases of the acquisition process (i.e, conceptual demonstration/validation FSD, production and deployment phases and during in-service evaluation). It addresses most of the front-end R&M design elements (stress analyses, FMEA, thermal analysis, derating, etc.), R&M growth testing, ESS and Failure Reporting, Analysis and Corrective Action System (FRACAS) and R&M Accounting Policy.

c. Funding Characteristics. The Services procure weapon systems with somewhat different R&M philosophies. Meeting the R&M requirements in a cost-effective manner, however, is a common problem for all programs. Structuring a R&M program for a weapon system that is being developed under severe budget constraints requires many trade-offs to obtain the desired balance between performance and R&M requirements. These trade-offs must be done early in the program to identify the elements that will have the highest payoff in enhancing the R&M of the system. To the extent performance requirements will permit, introduction of immature technology should be minimized. In other words, the use of proven technology and existing design where possible will minimize downstream problems.

Today's funding profiles, as shown on Fig. B-8, tend to drive technical decisions which can lead to poor initial reliability.

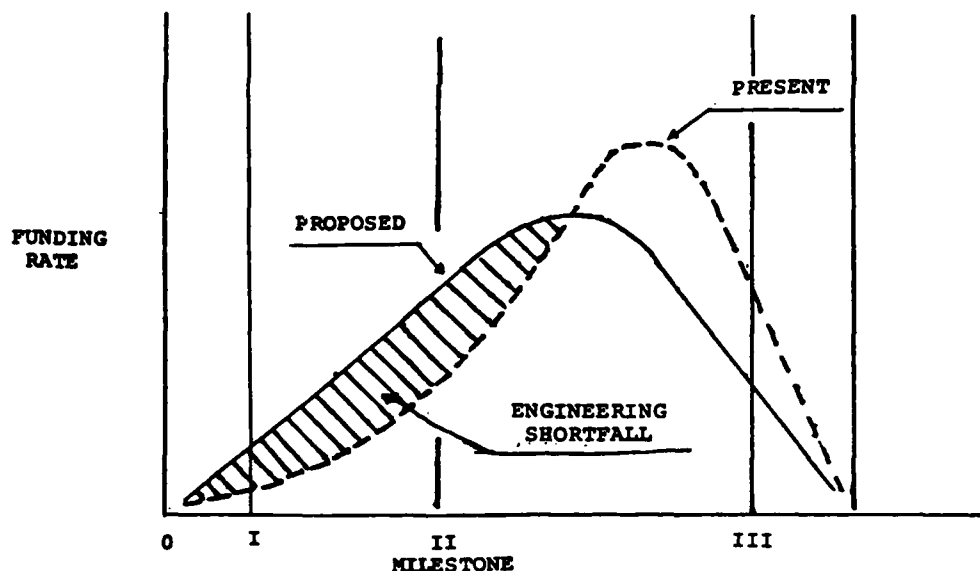


FIGURE B-8. Funding Profiles

The proposed profile is intended to reflect the need for early program funding. During these early phases, high-risk portions of the program should be identified and actions taken to minimize those risks.

Note that a significant amount of development funding is required prior to Milestone II, as well as some funding after Milestone III. This post-Milestone III funding will permit the engineering effort necessary to correct problems found after production begins.

The general shape of the actual Total Obligation Authority (TOA) profile for the FSD portion of the F-15, F-16 and F-18 programs is shown in Figures B-9, B-10 and B-11, respectively. Milestone events have been added to the figures to show how these programs were funded relative to the milestones. A comparison with the recommended profile shown in Figure B-8 tends to reflect the amount of concurrency in each program as well as how these programs were funded relative to the proposed funding profile.

For programs with severe budget constraints, consideration must be given to focusing on front-end design activities to develop high design potential and then planning for an extended R&M growth/maturation program, using data obtained from production and field usage to identify problems and establish design fixes. Costs of R&M testing (R&M Development and Demonstration) can be minimized by using data from all tests for R&M purposes and combining R&M test requirements with performance and environmental qualification tests. If results are to be achieved which are considerably better than those currently being experienced, a need exists to do some things differently. Starting a growth program with a more mature design and growing the diagnostics, simultaneously, is a promising approach favored by many experts on this study.

In the past it was not uncommon to begin growth testing with an immature design. Test time was wasted identifying the major

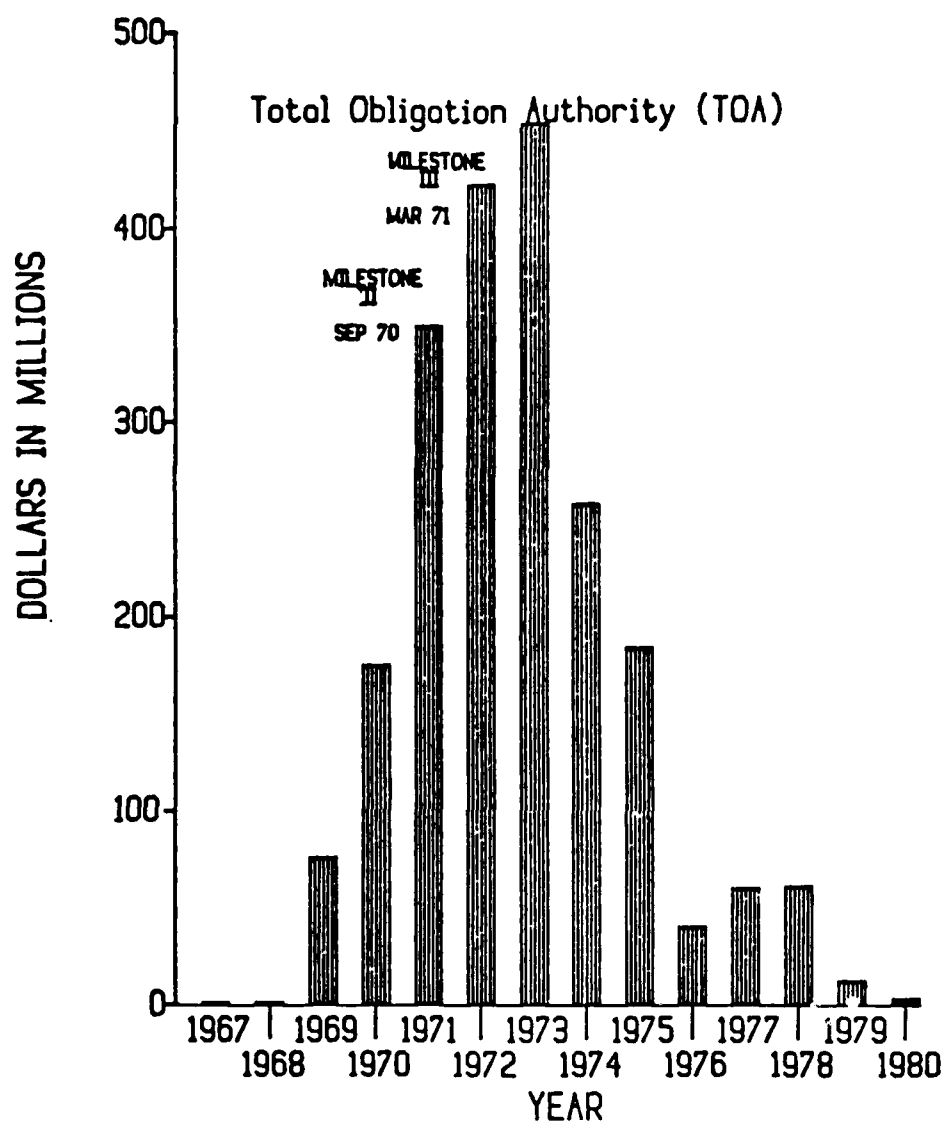


FIGURE B-9. F-15 Development Cost Profile

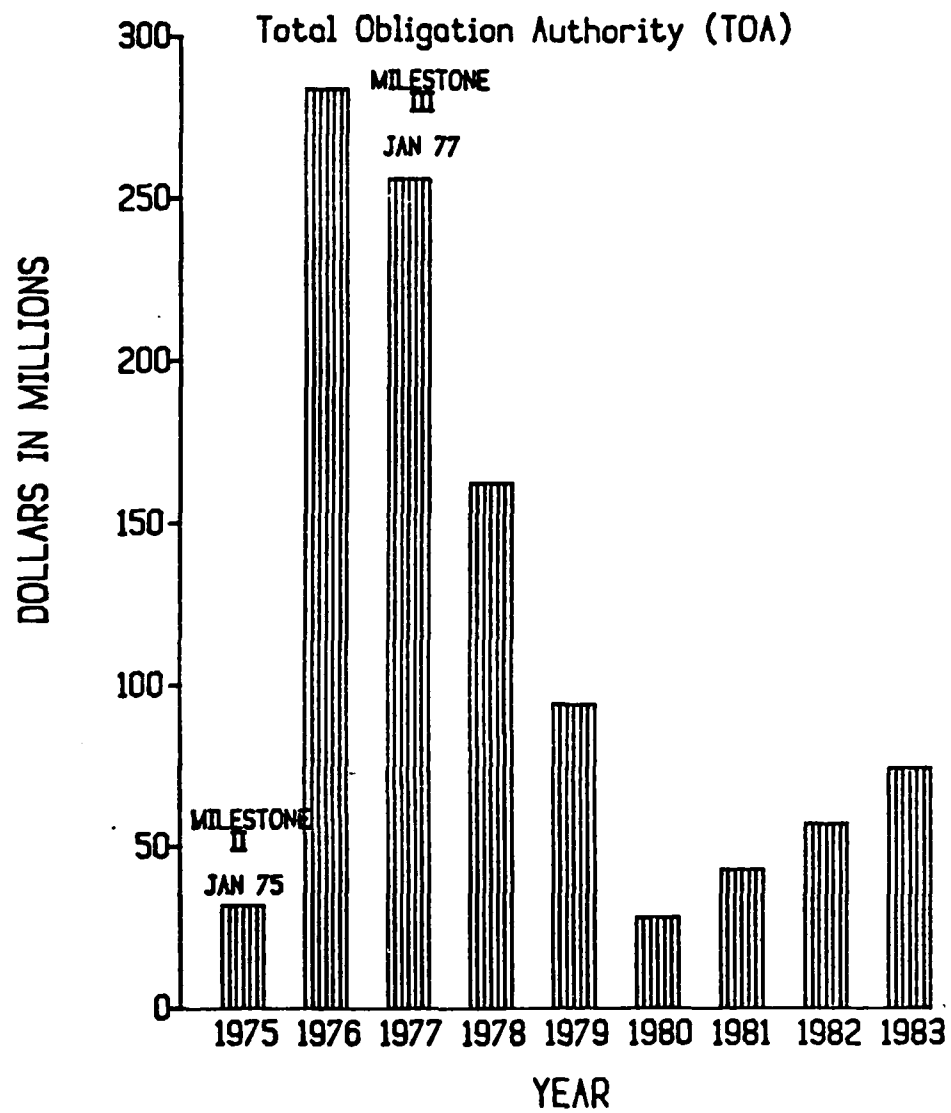


FIGURE B-10. F-16 Development Cost Profile

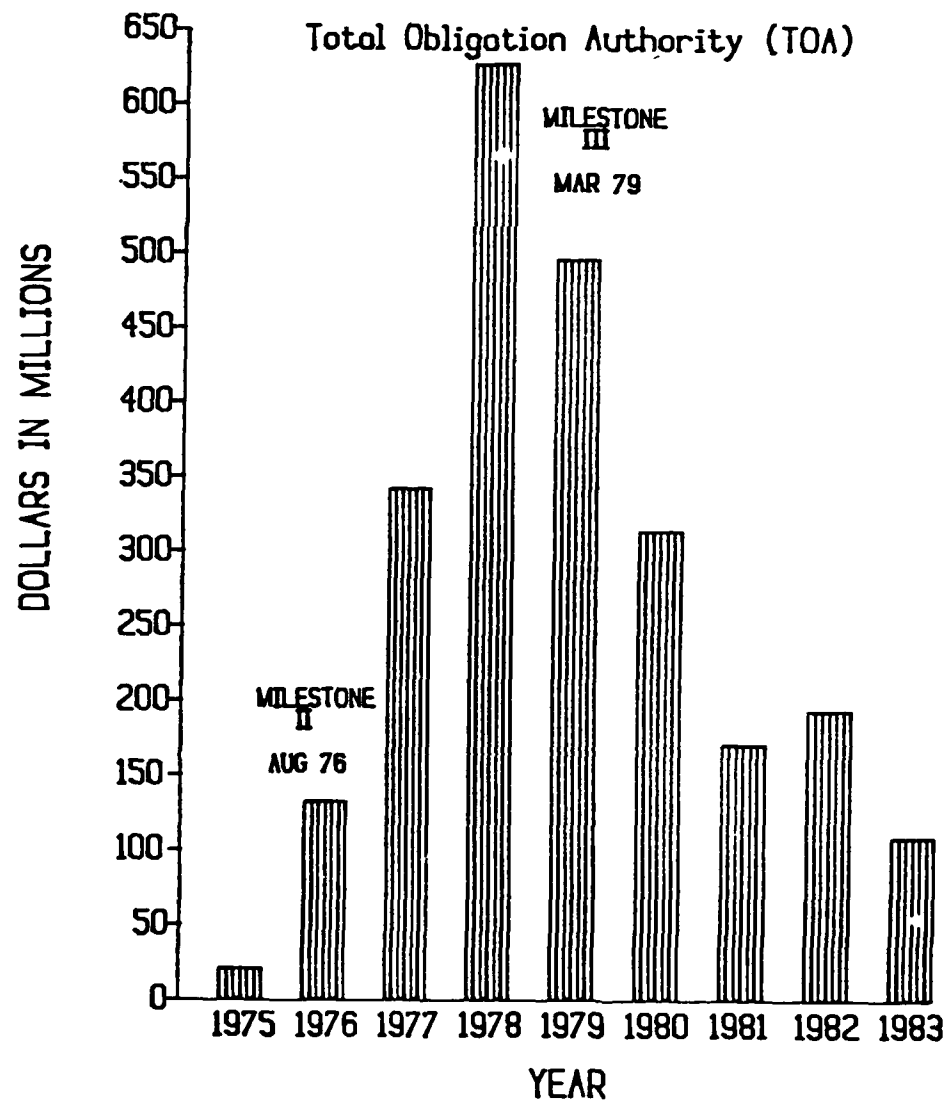


FIGURE B-11. F/A-18 Development Cost Profile

faults that could have been eliminated with a stronger up-front effort. This up-front effort would facilitate more efficient use of test resources to identify the latent problems that design analysis will not detect. The funding profile proposed, as shown in Fig. B-8, could facilitate this front-end effort. With the present funding profile, the designer's innovative and creative thinking can be severely constrained by schedule. His primary emphasis is to put a system together that functions with a minimum of effort and to develop a design which not only functions but also does so with a low failure rate. This constraint currently forces the designer or program manager to delay the development of a diagnostic system until well into the testing phase, a major problem identified by these case studies.

In order to make a major breakthrough in reliable systems, the funding profile proposed or one similar to it is probably mandatory. Not only does this make the growth and maturation phase workable but it also reduces the burden of test concurrency and would allow the growth programs to start with a system which, by current standards, would be equivalent to a second test phase system.

d. Acquisition Policy. The government acquisition policy must be considered when structuring a program. When the policy was one of "fly before buy" there was adequate opportunity to develop, test and fix problems before committing to production. The T700 engine program was a sequential type development but was concurrent with the Blackhawk and Apache programs (Ref. T700 Case Study, p. IC-15). The design and development of the T700 engine started with early component development work in 1964 and culminated with shipment of the first production engine in March of 1978, as illustrated in Fig. B-12. The success of the engine is attributed to early anticipation of future requirements in the component development efforts, validation of the

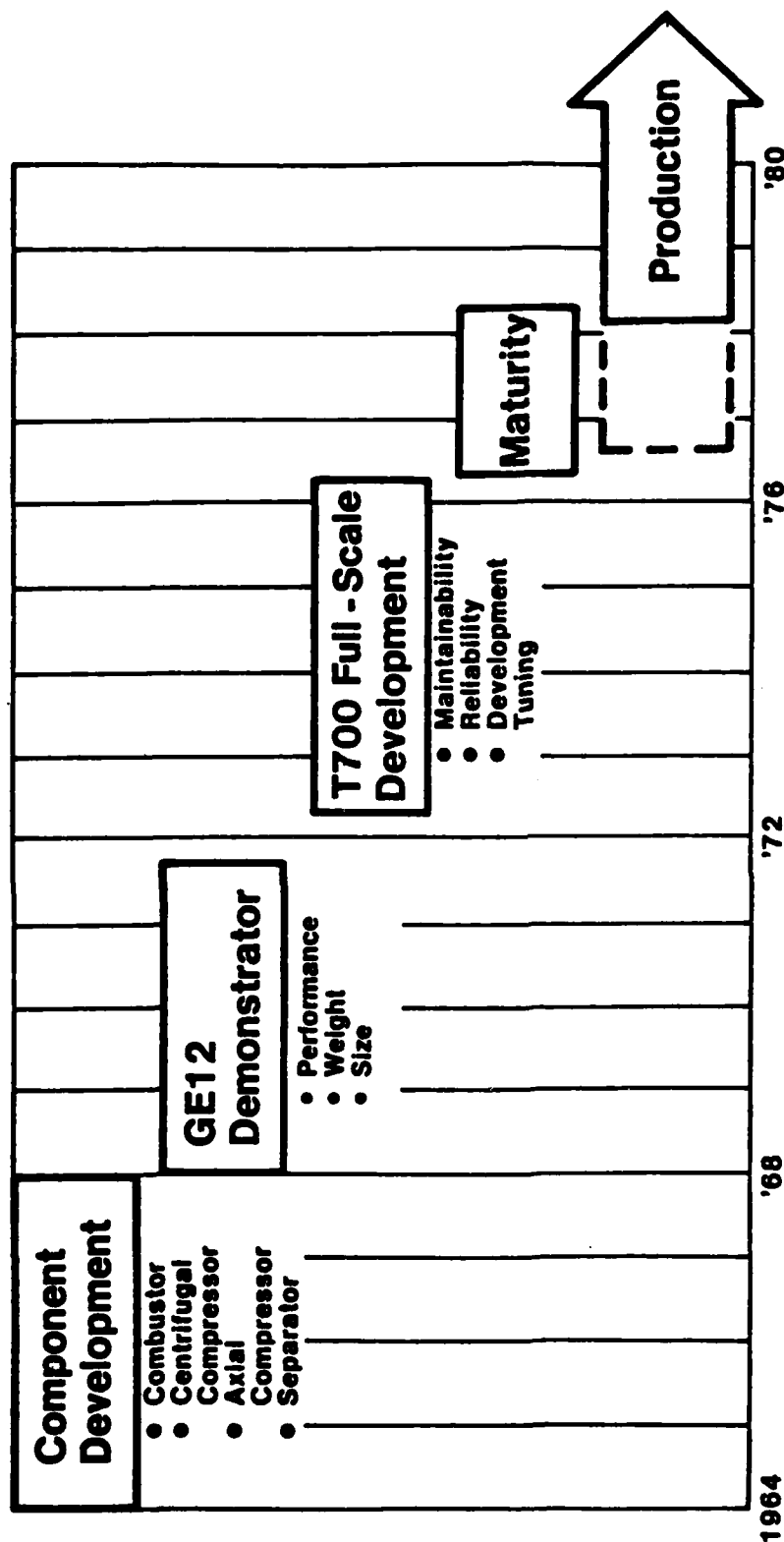


FIGURE B-12. T700 Engine Evolution  
(Ref. T700 Case Study, p IC-3)

115/3-15



technical requirement in a competitive engine demonstration program and concurrent engine and aircraft full-scale development efforts, as illustrated in Fig. B-13. A major contributor to the overall program success was adequate funding to complete satisfactorily each phase of the 12-year development process. Concurrent programs, such as the F-15, F-16, and F/A-18, must be structured so that R&M activities are implemented at the beginning of the program and are considered as important as performance requirements throughout the development cycle. As discussed in Section D of this appendix, R&M requirements can be met in a concurrent type program if the R&M design disciplines are enforced up-front and a R&M growth program is implemented extending throughout the FSD phase and into production. All R&M problems will not be identified prior to initial deployment but with a good R&M growth program the R&M field requirements can be met as early or earlier than in a sequential program. The F-15, F-16, and F/A-18, TPQ-36 and TPQ-37 were successful in concurrent development/production type programs.

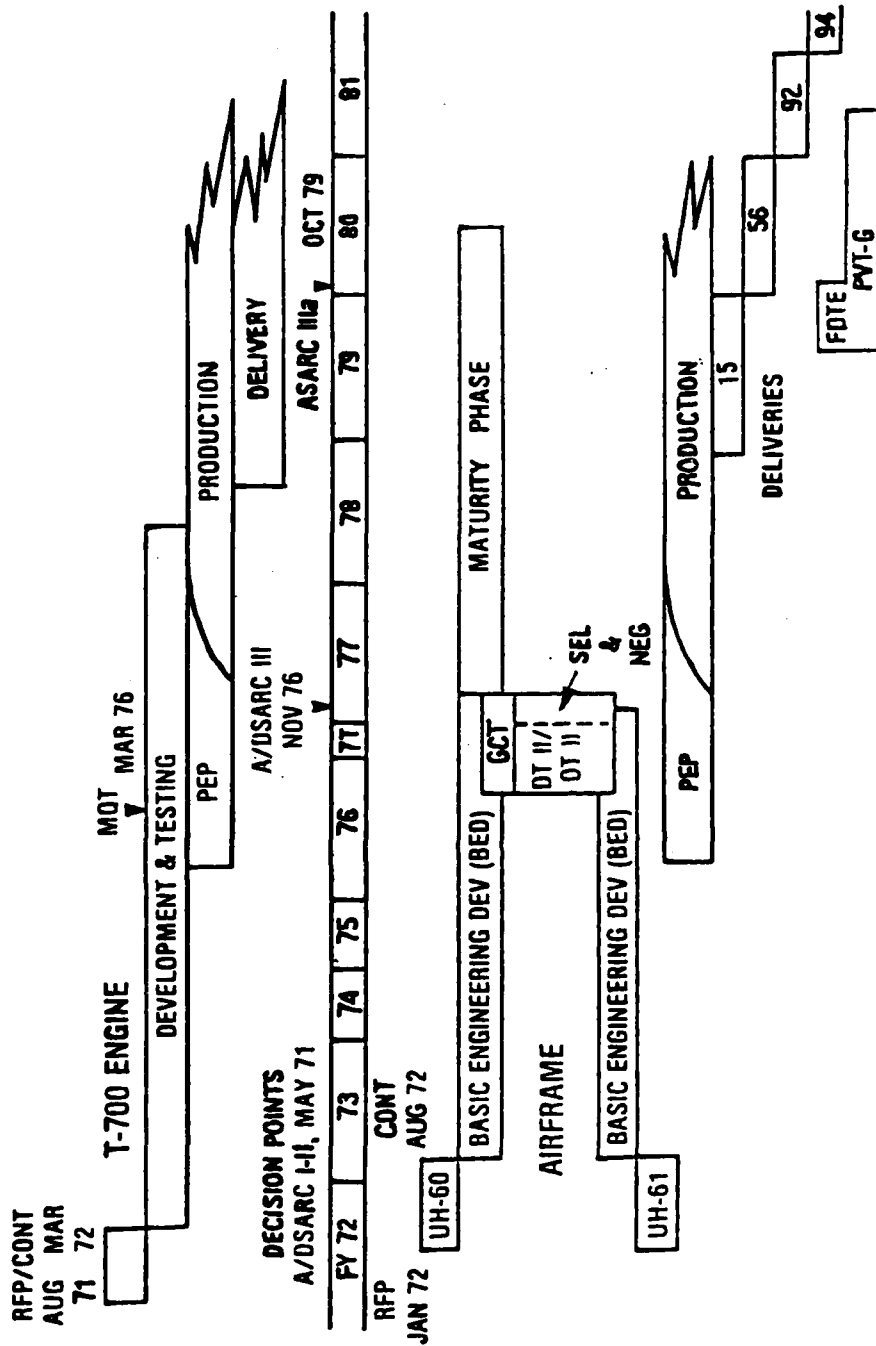


FIGURE B-13. Blackhawk Program Schedule

113A/7-13

## B. STRUCTURING FOR R&M IN WEAPON SYSTEM PROGRAMS

This section discusses the structuring and execution of reliability and maintainability programs as indicated by the results of the case study reviews and other information that was presented or obtained during the course of the study. To aid in the conduct of the case study reviews, the R&M program activities were divided into five major categories: contracting, management, design, manufacturing, and test and evaluation. These five major categories were used to provide the format for the following discussion on how to structure and execute successful reliability and maintainability programs.

A major problem confronting procuring activities responsible for R&M is the proper selection of key elements necessary for successful programs. This is not a simple task. Relative importance and applicability of R&M program elements will vary to some degree from program to program and phase to phase. Nevertheless, the following paragraphs provide some guidance and rationale to assess whether or not key program elements have been properly addressed. Those R&M program elements discussed in the following paragraphs were selected because of their importance and broad applicability.

### 1. Contracting

Seven elements will be examined in this section. These are: R&M requirements, mission profile establishment, life profile establishment, R&M failure definition, incentives, source selection criteria, and life-cycle cost consideration.

a. R&M Requirements. Acquisition programs must be structured so that full-scale development and production contracts contain R&M requirements, not goals, in order to allow R&M to compete

effectively for management support. To be truly enforceable, requirements must have contractually specified verification. R&M verification has historically been a problem area. It requires adequate definition of the quantity to be measured, the method of measurement, and the environment in which the measurement is made. Divergence of any of these factors from actual field application can result in significant differences between verification results and results in actual operational use.

(1). R&M Contract Goals versus Requirements. R&M contract goals do not receive proper attention. When R&M values were specified as goals, as was the frequent procedure a number of years ago, the technical performance requirements received higher priority in the decisions of management. The use of R&M goals placed R&M at a disadvantage with other system attributes that were specified as contract requirements. The result in many cases was lower than desired levels of R&M. To properly compete for contractor management attention and resources, the R&M numerics should be specified in the contract (specification or statement of work) as contract requirements as opposed to goals. Qualitative requirements should also be specified (particularly in maintainability). All contract requirements must have contractually specified verification to be truly enforceable requirements. The requirements must address (or recognize) any R&M growth that is planned.

(2). Developing R&M Requirements. Properly defined, realistic R&M requirements are fundamental to successful R&M development. Program R&M requirements establish the basis for determining the resources assigned to the task and the R&M approach during design, development and production.

(3). Testability Requirements. The establishment of testability requirements, particularly in the area of built-in-test, has evolved slowly over the past ten years. Most programs have followed the lead of their predecessors and have added little to the general knowledge of the procedure for stating requirements. Considerations that have been suggested to improve the statement of requirements for diagnostics include:

- BIT requirements should be stated in terms of system functions, i.e., can functions that are not performing properly be detected by the built-in-test system? This statement would replace requirements that address the detection of all part failures.
- BIT requirements should account for the criticality of the function or equipment. There is no logic to stating the same level of BIT for all avionics equipments in a weapon system without regard for the relative item criticality.
- BIT requirements should consider the type of system or equipment being addressed. The mechanization of BIT for a digital computer versus a video display is considerably different. The requirements should recognize this fact.
- BIT has two major functions--detection of a fault and isolation of the fault. These two functions are aimed at two different users. The operator or crew member needs to know that a failure exists. The maintainer needs to know where the failure is so it can be repaired. These two different aspects must be considered in the BIT requirements.

- Most BIT systems have monitoring that is done continuously and monitoring that is done only upon command from the crew or the maintainer. These aspects should have different requirements. This specific definition of requirements aids in focusing the designer's action to areas of criticality and need.

b. Mission Profiles. Mission profile development should begin in the earliest program phase and continue to some degree throughout the program. Detailed design analysis and decisions must be performed in the context of the expected system environmental conditions. If mission profile or profiles are not defined early in the program, then critical design decisions may not consider the expected operational stresses. Reliability and maintainability are functions of these operational stresses. Consequently, an accurate and relatively comprehensive definition of the anticipated use environment is necessary for the designer to have a reasonable chance to design equipment which will satisfy the operational need.

Mission profile definition should include:

- System utilization
- Maintenance concept
- Time-phase sequence of system operation
- Time-phase sequence and period of environmental conditions.

Profiles should be defined using the best available data, but it must be recognized that predicting system usage and environments is not an exact science. As the system is developed, continued effort must be expended to substantiate these projections and make any appropriate modifications. Systems with significant advances in capability over existing systems can result in unexpected mission profiles.

c. Life Profiles. Detailed design actions must also address the stresses that are projected for the system's life profile (Fig. B-14). The non-mission portion of a system's life profile can include design requirements that are not contained in the defined mission profile. The definition of the life profile must address all operational and support phases including those that may not be accurately definable by the system contractor. The unique aspects of the non-mission portions of the life profile need to be translated into design requirements. Profiles must address the total usage including dormant time, time waiting for the mission, maintenance time. Preliminary planning documents are usually not adequate or complete enough:

- Non-Mission Stresses

Result from:

- Transportation
- Handling
- Storage
- Test or Checkout

- Duration of Non-Mission Periods:

	<u>LIFE</u>	<u>MISSION TIME</u>	<u>PERCENT OF LIFE IN NON-MISSION TIME</u>
Missile Electronics	10-15 yrs	30 min	99.9%
Aircraft Electronics	15 yrs	4,000 hr	96.9%

FIGURE B-14. Non-Mission Portions of a System Life Profile are Significant in Stress Levels and Duration

d. R&M Failure Definition. The R&M requirements only have complete meaning if established in a defined context. Variations of failure definitions, time, critical failures, etc., result in wide variations of meaning of R&M parameters and inadequate communication between the government and the contractors.

The R&M requirements must be established in a defined context. They consist of the following elements:

- Quantified Parameter
- Parameter failure definition/scoring criteria
- Expected operational/field service conditions
- Definition of verification procedures.

These elements must be recognized as changes in R&M requirements. The definition of failure, man-hours, maintenance, operating time, critical failures, etc., must be completed before the quantitative R&M requirements are established. General definition must be made prior to detailed design activity if the R&M requirements are to have any impact on the design.

Contractual agreements for failure definition, etc., must be made which are mutually acceptable to customer and contractor. The definitions must be in writing and established at an appropriate point in the contract. Not all can be made at the front end of the contract.

Different definitions should be used to define operationally relevant conditions and to define contract chargeable conditions. The priority should be to define these two sets accurately for their two distinct purposes rather than compromising the separate accurate definitions for a single less accurate set. However, contract requirements must clearly support operational requirements.



e. Incentives. R&M contract incentives can aid in developing reliable and maintainable systems. Properly structured R&M contract incentives can be used to focus contractor management attention on critical R&M factors. R&M contract incentives are not substitutes for an overall R&M program, but rather contribute to a good program. The program must contain clear requirements and proper funding to accomplish required changes to the equipment. The R&M incentive approach to a particular program should be based upon the critical R&M parameters or characteristics for that system. Once the critical parameters have been identified the various incentive approaches must then be evaluated. Some approaches have their basis for measurement only in operational service (e.g., reliability improvement warranties). Other incentive techniques may be applied in any time phase (e.g., award fee). Careful attention should be paid to the selection and balance of multiple incentives to assure that they are compatible, and properly focused to achieve the desired result. Incentive applications should not be limited only to the design phase. The R&M incentives must be viewed in the context of the total incentive package on the contract to assure proper relative weight is given to R&M and that conflicts with other incentives do not exist.

f. Source Selection Criteria. The priorities used by the government in evaluating potential sources for products and awarding contracts have not substantiated the importance of R&M. The government source selection criteria has not consistently placed adequate priority on R&M (Fig. B-15).

	<u>TOTAL NUMBER OF PROGRAMS REVIEWED</u>	<u>NUMBER WITH R&amp;M IN SOURCE SELECTION</u>	<u>PERCENT</u>
ARMY	6	2	33%
NAVY	6	0	0%
AIR FORCE	<u>8</u>	<u>4</u>	<u>50%</u>
TOTAL	20	6	30%

(LMI Working Note: "A Documentation of DoD Strategies for Acquiring Weapon System Reliability and Support" Dec. 1982, pp. 2-2, 2-3, and 2-4.)

FIGURE B-15. R&M is not Consistently Used in Source Selection

The government's priority on R&M is reflected in:

- The RFP statement of proposal evaluation criteria.
- The source selection evaluation board weighting method.
- The final selection of a contractor.

The first of these can motivate the contractor to propose his best design or approach to the R&M. The latter two ensure the proper evaluation of the alternative R&M characteristics and the potential for selecting the best approach from an R&M standpoint.

Contractors will not attach high value to R&M until they see the government making selection of designs with good R&M features and rejecting ones that trade off R&M design features. R&M should be a major element in the evaluation.

g. Life-Cycle Cost Consideration. Life-cycle cost is one consideration in defining R&M requirements. A system's life-cycle cost is a function of R&M variables and can be reduced by selecting and achieving certain R&M requirements. Life-cycle cost analyses can be used to determine R&M levels that will result in reduced life-cycle cost. During design trade-off studies, LCC should be used as one factor to evaluate alternative designs. Life-cycle cost analyses must adequately consider other constraints such as readiness requirements and overall system effectiveness. During test and evaluation, R&M problems should be assessed against LCC impact.

## 2. Management

In the management area, three elements were examined. These were: planning, control and emphasis by government and contractor management, and the monitoring and control of subcontractors and suppliers. The need for management support of an efficient engineering change system is also discussed.

a. Planning, Control and Emphasis. Government and contractor top management emphasis can result in enhanced system R&M. Emphasis on R&M by government and contractor top management can provide a better balance between R&M and conflicting requirements such as cost, schedule, and technical performance.

Development programs contain many competing requirements for resources and management attention. Management emphasis on R&M must be evident to all levels of government, contractor, and subcontractor personnel to cause a balanced approach and appropriate consideration to R&M. Contractor management must be convinced that the government program manager considers R&M as important as other aspects, e.g., performance, cost and schedule. Most companies have the design tools and systems and will respond to R&M requirements if the priority on this area is evident. Government emphasis can be evidenced by source selection criteria, contract structure, incentives, willingness to fund up-front money for R&M, willingness to give R&M proper consideration in trade-off decisions. Direct involvement by customer and contractor top management is needed in reviews of the design and its R&M progress. Separate isolated R&M reviews will not lead to a balanced consideration with other contract requirements.

b. Monitoring and Control of Subcontractors and Suppliers. Subcontractor actions can be critical to producing a reliable and maintainable system. On many weapon systems, most of the

design, development and manufacturing is actually done by subcontractors. A major aircraft manufacturer recently estimated that only 7 to 10 percent of the weapon system unreliability was contributed by in-house design, while the other 90 percent to 93 percent was contributed by subcontractors. This makes it critical that the prime contractor and the government clearly communicate the importance of R&M to the subcontractors. The prime contractor must carefully structure and manage subcontracts to assure that weapon system and critical system R&M requirements are met.

The three aircraft radars examined were all critical R&M items in the prime contractor's weapon system. The radars were designed and developed by subcontractors. The radar subcontracts reflected the R&M requirements and the R&M approach contained in the prime contract. Where R&M contract incentives were included, they were also reflected in the major subcontracts. The incentives and the management priority placed on R&M by the government was understood and communicated to the subcontractors by the prime contractor and the government.

All programs required vendors to provide failure analysis and corrective action feedback on selected critical items.

c. Engineering Change Process. An expedited change system to rapidly approve and fund design changes for R&M would give the contractor tangible evidence of the government's interest in R&M. Valid and effective design changes for R&M often take one to two years to be approved and implemented after the production begins. Some never get funded. This indicates a low priority on improving system R&M. The ability to grow the R&M of the production system clearly depends upon the ability to make engineering changes. Many design change systems are frustrated by the government's long approval times and funding constraints.

The government's reluctance to modify this process is taken as an indication of a low priority on improving the R&M or other characteristics of the system. Decisions to correct this situation on individual acquisition programs would effectively demonstrate the government's priority on improving system R&M through implementing design corrections. Approval to retrofit approved changes during the course of contractor maintenance will also expedite the implementation of R&M improvements.

### 3. Design

In the very important area of design, nine elements were examined. These nine elements were:

- Development of design requirements
- Design alternative studies
- Design evaluation analyses
- Parts and material selection and control
- Derating criteria
- Thermal and packaging criteria
- Computer-aided design
- Testability analysis
- Testability verification and testing.

a. Development of Design Requirements. The allocation of system requirements to lower levels allows the designer and unit managers to have assigned R&M responsibilities. This allocation should identify any areas of unusual technical risk. R&M requirements must be translated into meaningful actions that the designer can understand. In the case of reliability, the designer cannot directly design to requirements such as MTBF. MTBFs must be translated into the selection of components and component stress levels. Usually, this is done by providing designers derating criteria, and part selection guidelines. Contractors should have a rational translation process.

The process of translating maintainability requirements into design actions is not as well understood, particularly in the area of built-in-test. Nevertheless, contractors should develop a rational process, derived from top-down considerations, to translate maintainability requirements into design guidelines.

Better testability tools are needed to communicate the BIT requirements to the designer. In the case of reliability, the designer cannot respond directly to requirements such as MTBF, but he can respond directly to items such as derating requirements

and parts selection guidelines. Similar design criteria guidelines are needed for the designer in the area of built-in-test. Possible areas are items such as components per test point, nodes per test point, frequency of examination, number of out-of-tolerances required prior to display of indication, etc.

Computer-aided design tools exist to help in providing rapid evaluation of the design for testability. These tools aid in the selection of test points, evaluation of partitioning and also allow the evaluation of the design and the test points using simulation of faults and BIT.

b. Design Alternative Studies. Trade studies have a significant impact in establishing the design baseline and in determining the R&M of the system. R&M are design attributes that must be evaluated through analyses. Design trade studies examine alternative designs and result in narrowing the range of expected or potential R&M performance.

An aggressively managed trade study program is directed at finding a proper balance between the many demands on the system design. This balance should attach appropriate importance to R&M considerations and risk to assure that alternatives which improve R&M are examined. All trade studies need to address the impact on R&M. The studies, at the appropriate level of detail, should be accomplished during all program phases.

c. Design Evaluation Analysis. To be most effective the R&M design evaluation analyses must be an integral, timely part of the detailed design process. Otherwise, they merely record information about the design after the fact. The later in the process needed changes are identified, the more costly in terms of time and schedule they become and the lower the probability that they will be incorporated.

The design evaluation analyses are best done as an integral part of the detailed design, and by members of the design team when practical. A common flaw in some R&M programs is to have the R&M analyses separated from design activity by time (in this situation the analysis merely documents the characteristics of the design without affecting the design chosen), distance or organization. Separation by organization can have positive or negative impact depending upon the organizational factors (and personalities) involved. The timing and the credibility of these analyses must be such that they are accepted as part of the design evolution.

The role of R&M analyses in design changes can often be an indicator of the importance placed upon these tasks by the design team and contractor management.

A technical "design point" should be defined and specified for the design evaluation analyses. The design evaluation analyses are inconsistent (or inaccurate) if varying environmental conditions are assumed for different analyses.

The design evaluation analyses include stress analysis; worst case analysis; numerical predictions; failure modes, effects and criticality analysis; and sneak circuit analysis. Some of these (e.g., predictions, stress analysis) are dependent on defined environmental and operating conditions.

Conditions selected for the individual analyses may be different.

- The result is inconsistent analyses on a single development program
- Also, it is difficult or impossible to do comparative evaluations between programs.

Some analyses might be done at multiple design points (heat loads, operating modes, cooling air flow rates, etc.) to completely examine the likely system conditions.



d. Parts and Material Selection and Control. A well-defined, properly-executed parts (and material) control program can reduce one major source of potential reliability problems, piece part failures. A parts control program restricts the use of parts to those having well-established reliability characteristics and provides a methodology for managing exceptions to the control program.

Restricting appropriate classes of parts to well-understood, high-volume components with increased assurance of part quality can contribute significantly to producing a reliable product. The approved parts list must be available before the designer is ready to select components. The authority for granting exceptions to the control procedure should be well-defined and monitored to assure that exceptions are not granted too freely.

e. Derating Criteria. Most development programs impose, as a requirement, derating criteria. The derating criteria should be part of a derating program which establishes management requirements and controls.

- Derating criteria should not be blindly applied to all components. Components have different system criticalities and reliability sensitivities to derating and may require different derating criteria.
- Exceptions should be justified on the basis of cost, lack of technically acceptable substitute, etc.
- Compliance with critical derating requirements should be verified.

(1). Derating Parameters. Single parameter derating criteria can result in inefficient or inaccurate derating. Some development programs have used simplistic, one-parameter, derating criteria. Most electrical and electronic components depend on a combination of parameters to determine stress levels. For example:

- Linear ICs depend on
  - Supply voltage
  - Input voltage
  - Output current
  - Maximum junction temperature.
- NPN transistors (Fig. B-16) depend on
  - Case temperature
  - Total power dissipation.

Derating criteria must be based on all essential parameters and allow trade-offs between the levels of each parameter. (See RADC Report TR 82-177).

(2). Exceptions to Derating Criteria. Exceptions to derating guidelines should be tightly controlled. Unnecessary exceptions or too numerous exceptions result in parts that are overstressed or stressed beyond the intended limits.

Most development programs impose an acceptable derating criteria. The derating criteria should be part of a derating program which establishes management requirements and controls. Higher part stress results in part from lack of control of the exceptions or deviations to the derating criteria.

#### f. Thermal and Packaging Criteria.

Thermal-packaging criteria are critical to the R&M success of the design. Temperature level and temperature rate of change are the principal sources of stress which affect component reliability (see Fig. B-17). The thermal conditions that equipment parts are subjected to are dependent on the operating environment and packaging/cooling design. The choice of cooling design can significantly impact different component temperatures and/or rate of change of temperature. Cooling methods include:

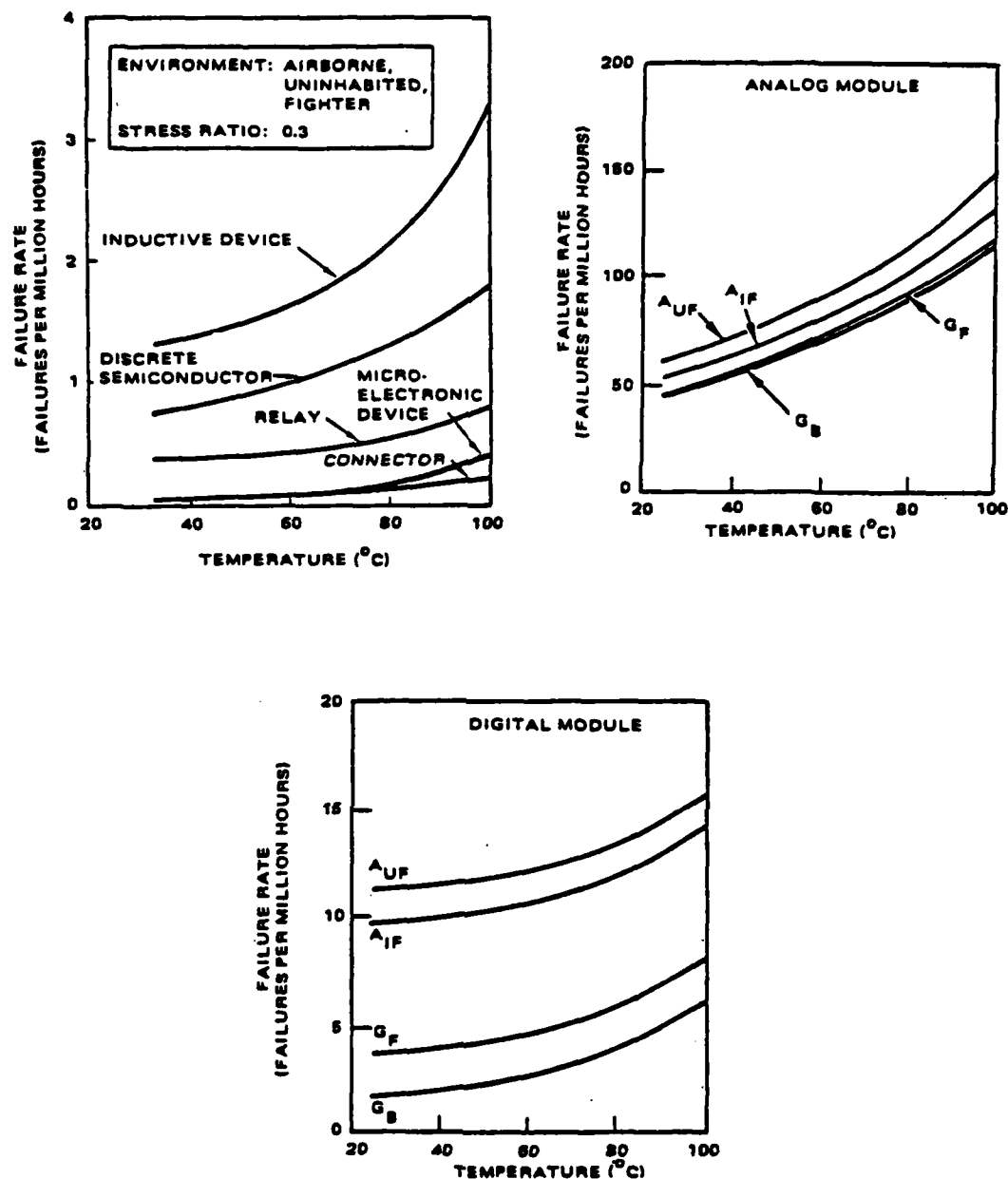


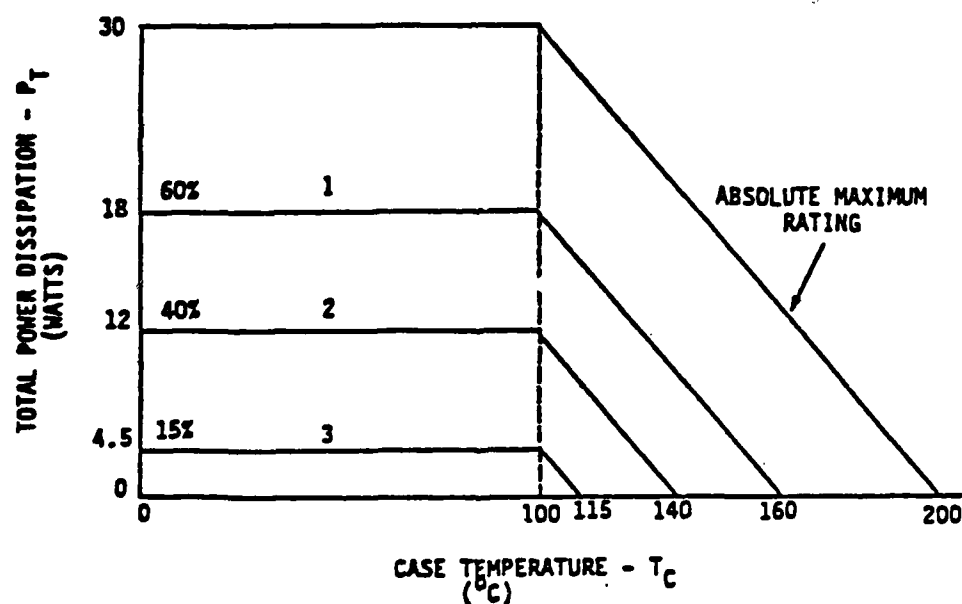
FIGURE B-17. Temperature Drives Component Failure Rate

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# LINEAR DERATING

PARAMETER	LEVEL		
	I	II	III
SUPPLY VOLTAGE	0.70 (1)	0.80	0.80
INPUT VOLTAGE	0.60	0.70	0.70
OUTPUT CURRENT	0.70	0.80	0.80
MAX JUNCT. TEMP (DEG C)	80	95	105

- (1) Designing below 70% of the supply voltage may operate the device below the recommended operating voltage.



Derating for NPN Transistor Type  
2N3997 By Junction Temperature Only

FIGURE B-16. Multiple Parameters for Derating  
(from RADC Report TR-82-177)

- Direct cooling;
- Cold walls or edge board cooling, and
- Flow through cold plate cooling.

(See RADC Report TR 82-177).

After the equipment is produced, a thermal verification test is required to assure that the thermal criteria have been met. The test should be run using a simulated worst-case mission environment.

Specific thermal analysis and thermal analysis verification requirements should be specified to assure compliance with thermal design conditions.

g. Computer-Aided Design. Computer-Aided Design (CAD) techniques can help produce reliable and maintainable equipment. R&M characteristics are attributes that require evaluation of specific designs. CAD techniques can allow the designer to quickly and efficiently evaluate design alternatives, allowing more design alternatives to be evaluated in more detail. This promotes development of a design that satisfies a number of design constraints and optimizes other design features.

Computer analyses are tools that in an automated manner attempt to optimize a characteristic of the design, or other automated analyses. CAD for R&M can consist of R&M predictions that the designer can evaluate, the identification of overstressing, sneak paths, and malfunction choke points, as well as automated decisionmaking that forces the design alternatives to meet certain constraints. CAD techniques have been used to perform thermal analysis (Fig. B-18). The priority of R&M in the CAD process should be balanced with technical performance, weight, etc. Viable, cost-effective recommendations should result from the process. Integration of R&M tools into the CAD system will occur when customer and contractor management are motivated toward R&M considerations.

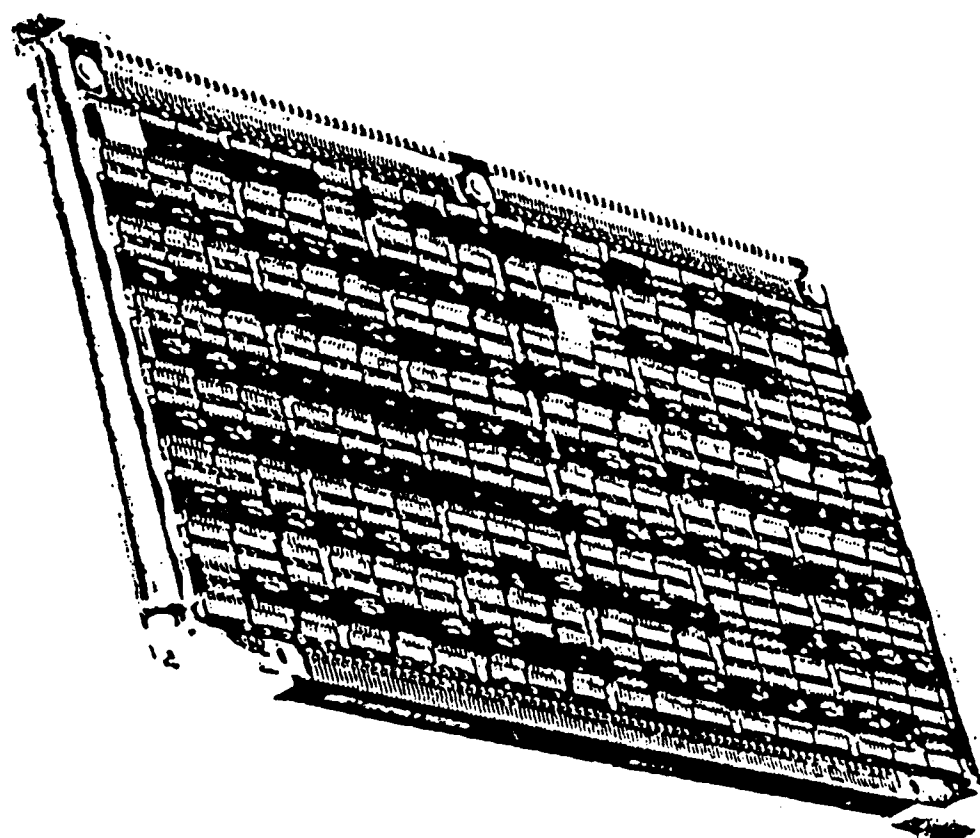
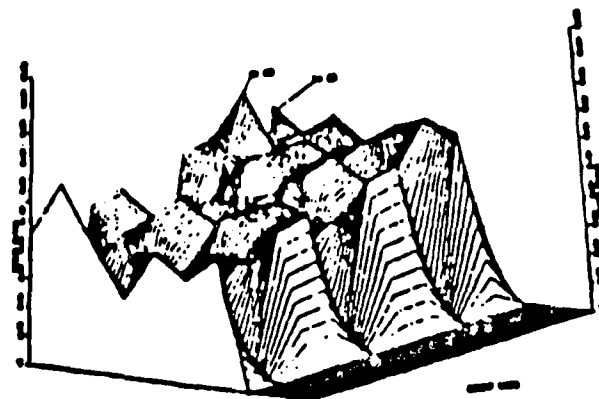


FIGURE B-18. Computer-aided design was used to optimize board layout considering thermal stresses

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h. Testability Analysis. Testability analysis should be used to define diagnostic requirements before the detailed design. During the detailed design, test point analysis and nodal analysis for partitioning should be major inputs to the layout/packaging design. Analyses of projected BIT performance and fault simulation studies should be used to evaluate the progress toward the BIT objectives and as inputs to a BIT maturation program.

Testability analysis needs to relate to the actual conditions that will occur. Recent technical papers have highlighted the difference between "hard" failures that are "permanent" and faults that are transient and temporary. Transient and temporary faults are the result of unexpected conditions in input data, unusual or unexpected environment, timing incompatibilities or equipment incompatibilities. These occurrences result in temporary equipment problems and may be the forecast of permanent failures that will happen after more equipment operation.

The current methods of BIT or testability analysis are for the most part based upon the output of the reliability failure modes and effects analysis. In many FMEAs only permanent failures are examined. Some make an attempt to examine the temporary faults, but in most cases the quantity of unexpected faults is significant when compared to the fault categories that are addressed by the analysis.

i. Testability Verification and Testing. After the equipment is produced, there is a need for verification of the BIT design. Even prior to the beginning of equipment production, there is an opportunity to conduct equipment simulations to evaluate the status of the BIT design. Verification should continue through monitoring of the actual performance of the BIT as the system is used and tested. Because the normal system operation may not provide the quantity of faults and failures that are required to validate the BIT there should also be an assessment based upon

the insertion of faults. The magnitude of this program and the method used to generate the list of faults to be inserted determines the worth of this program. To insert failure modes that are expected and well understood will only give a partial assessment of the performance of the BIT in operation. The fault conditions that are experienced in the "real world" may be quite different from those generated in engineering analysis. This is one reason why most BIT development programs require a period of BIT maturation during early operational use.

#### 4. Production

In the production area, two elements were examined. These were environmental stress screening of parts and equipment and the use of failure reporting, analysis, and corrective action systems.

##### a. Environmental Stress Screening of Parts and Equipment.

An environmental stress screening (ESS) program can substantially reduce the number of latent defects in parts and defects due to workmanship in delivered hardware. ESS programs were effectively applied on the aircraft radar programs to address defects at the parts, assembly, box and system level.

The use of ESS as part of the receiving inspection of piece parts can be justified economically for some part types. Engineering judgment and/or evaluation must be made as to which specific screens will be most effective and/or necessary for specific part types. The receiving screens supplement screening programs that are normally applied at the part manufacturers.

With the limited historical experience, it is important for screening programs to remain flexible. Control of screening details should allow for adjustments as production proceeds, with government control of some final result (system level



burn-in with a failure-free period might be such a criterion). It may be necessary for screens used during the assembly of development units to be structured for a different class of defects than those for high-rate production.

b. Failure Reporting, Analysis and Corrective Action System.

The use of failure reporting, analysis and corrective action system (FRACAS) is an essential part of development and of reliability growth. Problems or failures must be documented, analyzed and corrective action taken for reliability growth and maintainability improvement to occur.

Problems or failures manifest themselves in a variety of ways. These include catastrophic failures and out-of-tolerance drift. Causes can include operator error, overstress, handling damage, spontaneous failure of piece parts, aging, and degradation. Appropriate effort is required for recognition, diagnosis and correction of these failures at the earliest possible phase in a product's life-cycle. Normally, FRACAS implementation should start about mid-demonstration and validation phase and extend through FSD and production. Cost in dollars and delays increases by orders of magnitude if the defect is allowed to manifest itself at higher levels of assembly or later in the life-cycle.

Potential problem identification and resolution is the most productive effort because the design can be changed more easily before it is released for production. Failures must be documented in a closed-loop tracking system to assure that all events are given appropriate attention and corrective action is considered.

5. Test and Evaluation

In the test and evaluation area, five elements were examined. These five elements were design-limited qualification testing,

reliability growth testing, demonstration testing, operational test and evaluation, and in-service assessment. The FRACAS system must be used for all tests to provide adequate feedback to the design engineer.

Most testing can be structured to provide valuable R&M information. To the maximum extent practical, every test should be viewed as an opportunity to assess and improve R&M. Certainly, from the time that any reasonably representative hardware is built and tested, reliability and built-in-test data ought to be collected, analyzed and acted upon. This includes development tests of all types as well as various qualification tests. Differences in equipment configurations and test environmental conditions will complicate assessments, but these problems do not outweigh the value of the opportunities to assess and mature R&M.

a. Total Program for Reliability Growth. A well-structured reliability growth program can be very effective in the development and production of a reliable system. Good design practices cannot totally eliminate problems. A growth program to identify problem areas and develop changes to grow the equipment reliability and substantiate improvements is necessary. Different tests in the development program produce different data as far as failure modes, environmental conditions, operating modes and configuration. A reliability growth program should use data from all test and operational sources. The program should be structured at the beginning to treat every failure or operating anomaly as a potential reliability growth opportunity. A single program should examine data from engineering development tests, integration tests, qualification tests, reliability demonstrations, production tests and operational tests. The growth program should continue into early field operation with contractor personnel at the operational sites. Resources and organizational structure must exist to pursue the results of the growth program

data analysis. Additional discussion on a total growth program is contained in the main report.

b. Design Limit Qualification Tests. Design limit qualification tests can be used to obtain R&M data. Qualification tests expose the design to conditions and operating modes that may not have been seen previously. Engineering data from these tests provide information on operations in these environments.

This test phase is usually not thought of as an R&M element. Some programs used qualification test data for reliability and maintainability engineering purposes. These tests examine the capability of the design (normally one sample) to meet the performance requirements at the design limit (normally for a short period of time or for a short performance test). The inter-relationship and sequencing of these tests and R&M tests can be critical to assure that the final design is adequately tested. The failure data (and diagnostic data) from these tests can be valuable since it will be some of the earliest data available. Design changes made later in the program must be evaluated as to their impact on the results of the design limit tests.

c. R&M Development Testing. A well-structured growth or maturation program can be very effective in the development and production of a reliable and maintainable system. A growth program to identify problem areas, develop changes, and substantiate improvements is necessary. Control of equipment configuration and test environment may require dedicated growth test articles. This will probably be true of avionics equipment. However, for equipment such as fixed ground electronics it may be possible to combine the necessary features of a growth program with other testing.

(1). Timing of Reliability Development Tests. Reliability development testing is more valuable if conducted relatively early in a development cycle. The relative contribution of reliability growth testing is a direct result of where the growth test is placed in the sequence and timing of the tests.

Reliability development testing can be a very effective task in the development of reliable complex equipment. This testing should be viewed as a "designer tool" to provide information on the design's capabilities, identification of problem areas and effectiveness of corrective actions taken. If performed early in the development cycle, this test can provide relatively large amounts of reliability information in a defined environment with good engineering controls.

If the reliability development test is late in the schedule, then the data may be of limited value because of the magnitude of data obtained from other sources.

The test plan, environments, number of test units, equipment operating sequence, procedures for failure analysis and corrective action, time phasing with the rest of the development program are all critical to the contribution of the growth test. Management's interest in the progress of the growth test can be a positive factor in keeping the growth test on schedule.

(2). BIT Development Tests. The maturation of the BIT system is dependent upon acquiring engineering data on the actual faults that the system is experiencing, the opportunity to eliminate these faults and the potential for the BIT system to detect and isolate these particular faults if required, and the elimination of "unnecessary indications" of failures or faults that do not affect the system performance. The length of time required for this maturation program depends on the quality of the data being collected. When compared to reliability growth testing, which used test hours as its basis, BIT development testing should use the number of faults experienced as its basis.

The quality of the data also depends upon the realism of the operation and environment that the system is exposed to during the maturation phase. If significant areas of the operating envelope are not examined, then many of the potential faults will not be identified or corrected. Every opportunity to exercise and evaluate BIT should be used in this process. Nevertheless, program results to date indicate that strong consideration should be given to extending planned BIT maturation into the operational phase. Presently, the data collection system for operational service is not adequate to support BIT maturation, making correction of BIT problems very difficult. A planned operational effort including special data collection could be very valuable.

d. Demonstration Testing. The purpose of demonstration testing is to provide a statistically significant measure of compliance with specified R&M requirements. Demonstrations should be included as an integral part of a comprehensive test program designed to provide leverage, not only for design improvements through incorporation and verification of corrective actions, but also for the basic design effort by the contractor knowing that the demonstration will be run and must be passed. Demonstration requirements increase management visibility and emphasis on attainment of specified values. Reliability demonstration during development should be followed by demonstrations of production reliability to assure correction of production problems not related to development, and attainment of higher specified reliability requirements consistent with production hardware.

The procedures selected for demonstrations should be consistent with the R&M program risks. For example, a ground electronics program using mature technology, in a well-defined environment, with a growth program and a reliability improvement warranty may warrant only a period of carefully controlled, all equipment data collection and subsequent analysis. On the other hand, customer

risks associated with a complex, airborne fire control radar would probably warrant the use of dedicated assets under more controlled conditions for the data collection effort.

In any event, to obtain the maximum R&M benefit, demonstrations must be tied to other development activities such as a closed-loop failure reporting and correction system to provide feedback to the designer so that changes can be implemented to improve the design. Demonstration tests should be integrated into a total growth program. Additionally, the selection of procedures to be used for production demonstrations should include consideration of the timeliness of the measurement, e.g., a lot of equipment with problems may be delivered to the customer if tests are lengthy and infrequent.

e. Operational Testing. Operational testing is the means by which weapon system performance and supportability characteristics are evaluated. Weapon system operational effectiveness and operational suitability including R&M factors should be evaluated numerically. The detailed results from operational testing must be fed back to the design team.

f. In-Service R&M Assessment. In-service assessment and corrective actions have been shown to be essential in achieving the R&M potential of the design. From the case studies examined, most contractors initiated a field monitoring program to assist in identifying problems and their cause.

Once a system is introduced into the operational environment, the environment (including operating and maintenance personnel) and full-rate production may introduce a new set of R&M problems that must be identified, analyzed, and corrected. These early production systems usually result in a large number of engineering

changes. In-service assessment required:

- Planning
- Assignment of engineering resources (including on-site contractor personnel)
- Selection of a capable R&M data system.

Programs that did not plan for in-service assessment generally ended up initiating such a program because of demands to identify and solve field problems. Government managers must recognize the need for this activity and provide the necessary resources.

In summary, a high quality of R&M data should be acquired in the early pre-deployment and deployment time periods until acceptable R&M is obtained. This can be achieved in a reasonable period of time by an aggressive failure analysis and corrective action program. For already fielded systems, a periodic, comprehensive sample data collection program may be desirable.

### C. INTERRELATIONSHIPS AND DEPENDENCIES OF THE ELEMENTS FOR SUCCESSFUL PROGRAMS

The purpose of this section is to discuss how R&M elements interact and fit together to support operational reliability and maintainability. Clearly, these case studies pointed out that combinations of elements, not individual elements, were responsible for the program's success. An example in point is that a good stress analysis individually will not make a successful program, but its omission may significantly reduce the probability of the program being a success due to its impact on other program elements reducing their effectiveness.

To ensure that the overall program is efficient and effective these interrelationships and dependencies must be considered. The following sections provide discussions of interrelationships and dependencies in three categories: overall program structure, design, and schedule.

#### 1. Overall Program Structure

A typical overall program structure from these case studies is shown on Fig. B-19. A program starts with the mission and life profiles and source selection criteria.

Progression down the chart represents a time sequencing of events for an overall program. Only major events are shown. Actual elapsed time between events varies from program to program, but the relative sequence remains similar. Arrowheads represent the flow of information to complete the process. This flow is not a new revelation, but does indicate that the same basic process is used throughout industry. These case studies do indicate that there are key areas of interrelationships and dependencies that should be addressed.



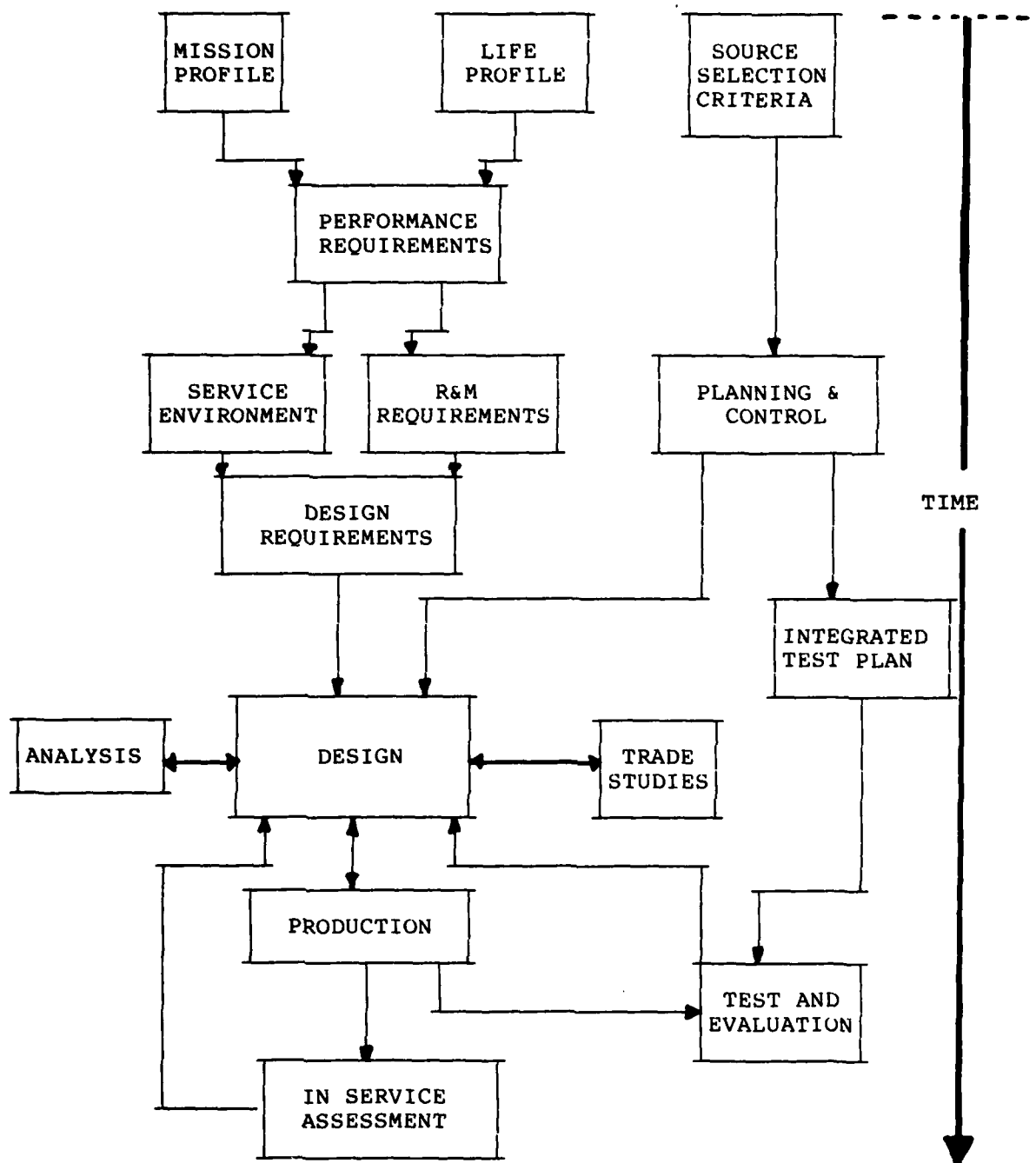


FIGURE B-19. Major Program Element Interrelationships and Dependencies

First, in order for the contractor to satisfy the customer, the requirements must be valid, realistic and clearly understood by both. If this is not true, the program runs a high risk of not satisfying the customer needs. In the case where the contractor understands what he is told, but the customer does not really know what he wants, the contractor can do an outstanding job and still not produce an acceptable system. In the other case, where the contractor does not understand, he has little chance of producing a product that meets the customer's requirements.

Establishing realistic mission and life profiles, LCC and DTC considerations, quantitative and qualitative requirements, and source selection criteria are vital to promoting understanding and acceptance of the operational R&M requirements by both customer and contractor. The successful programs studied benefited from this process. Of special note are the T700 engine for the Blackhawk helicopter, which led to a highly reliable and maintainable system; the F-16 radar, which has surpassed operational R&M projections; and the F-18 radar which has exhibited high initial reliability.

Second, participative management and individual and company motivation play a major role. It is not enough just to accomplish certain tasks. The right tasks must be done well and completed at the right time. Planning, control and management emphasis, design participation, monitor/control of subcontractors and suppliers, process control, incentives, and CAD/CAM all contribute to getting the right things done well and on time. The complexity of the acquisition process, combined with the complexity of the systems being developed present a formidable challenge. Incentives can play a major role in achieving high operational R&M provided that they are compatible with performance requirements. They will provide an environment to motivate the contractor to do his best.

Third, program risks must be managed. This means that a continuous assessment process must be initiated and problems identified and fixed at the earliest practical time. R&M failure definitions, dedicated test assets, design evaluation analysis/reviews, design limit qualification testing, demonstration testing, operational test, and in-service evaluation are all necessary elements of this assessment process. To accomplish this assessment, a comprehensive growth program must be planned and executed. A key to providing R&M growth is a good failure/corrective action program. All analysis and evaluation tools must be used to manage and control program risks.

The key to implementing these tools is a R&M growth program that includes the results of all testing. A test-analyze and fix (TAAF) philosophy applied throughout the program and continued into field operations will provide the maximum benefit.

Failure definitions which form a part of the standards against which progress is measured must be carefully constructed. Dedicated assets facilitate design verification and the timely identification and correction of problems. Design evaluation analysis/review promote a disciplined design process and provide for early incorporation of corrective action when it is less expensive to make changes. Design limit qualification testing provides an assessment of the design in environmental extremes. A failure analysis/corrective action program will provide assessments of the cause of problems and help to determine what corrective actions should be incorporated. This also aids in establishing the effectiveness of the corrective actions. The remaining elements assess operational R&M in progressively more realistic environments and usage. Properly used, each of these elements contributes to keeping program risks low. The successful cases studied used these elements well. They identified most problems early and fixed them before the fixes became too expensive to implement.

These cases studied showed that the combination of areas discussed above was what made the programs successful. Neglect of any of these areas invites problems. Decisionmakers must recognize the interrelationships and dependencies and avoid arbitrarily constructing and implementing R&M programs. Selected elements must be coordinated to ensure that both the customer and contractor clearly understand what is needed, that the process is well-managed by both customer and contractor, and that the assessment tools are sufficient to provide management the information necessary to control program risks.

## 2. Technical/Design Dependencies

As at the higher level of consideration, there are numerous important interrelationships between the R&M related activities in the design process. It is important for decisionmakers to have an appreciation for the extent of these dependencies when they are making tough decisions dealing with the allocation of scarce program resources.

Findings from these case studies show that, in general, all the analyses identified on Fig. B-20 were accomplished at various phases during the design process. In some cases, the analyses were not done as early as one would desire, but the results were available to influence the design process. Actual detail timing was difficult to identify since many of the analyses are an iterative process. It was concluded that most of the analyses had been done in a timely manner except for the BIT and ATE analysis. This had not been given as high a priority and therefore its development and maturing was coming later than desired.

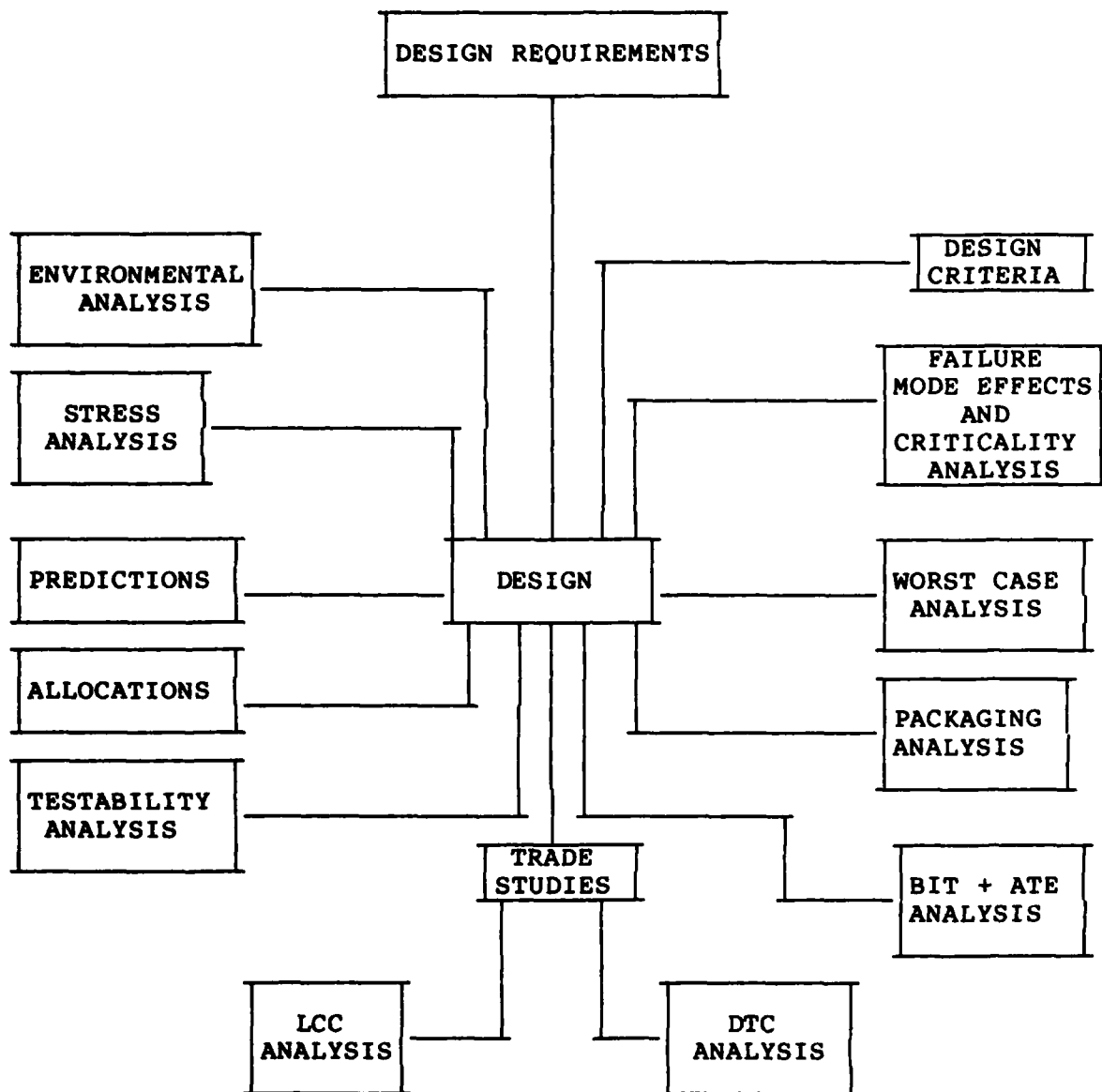


FIGURE B-20. Interrelation on Design Elements

In many cases decisionmakers are faced with resource shortages and are tempted to cut out or severely restrict some elements of the R&M-related design activities. Done without an understanding of the interrelationships, this could be disastrous. Consider the following illustration. Reliability predictions are a measure of a design's potential and are used to assess capability to meet allocated design requirements. The reliability prediction (Fig. B-21) requires knowledge of part selections and stress levels. Hence, a good prediction requires an information flow as depicted by the arrowheads. It includes a stress analysis which is in turn dependent on a thermal analysis for component temperature information. The thermal analysis requires cooling system information which in turn must have environmental input information from the mission and life profiles; without the stress analysis, the reliability prediction would require many assumptions which could seriously impact its accuracy. Without the thermal analysis, the stress analysis could be significantly in error; this again impacts the prediction and the design itself.

The point is that deletion or constraint of any of the related elements could significantly impact the outcome of the whole effort. Decisionmakers must explore the interrelationships present in their program and assess the probable impacts and consequences prior to making R&M program decisions.

### 3. Schedule Dependencies

Equally important to the inclusion of mutually supporting R&M program elements is the scheduling of all R&M elements. Timeliness of information may be critical to program success.

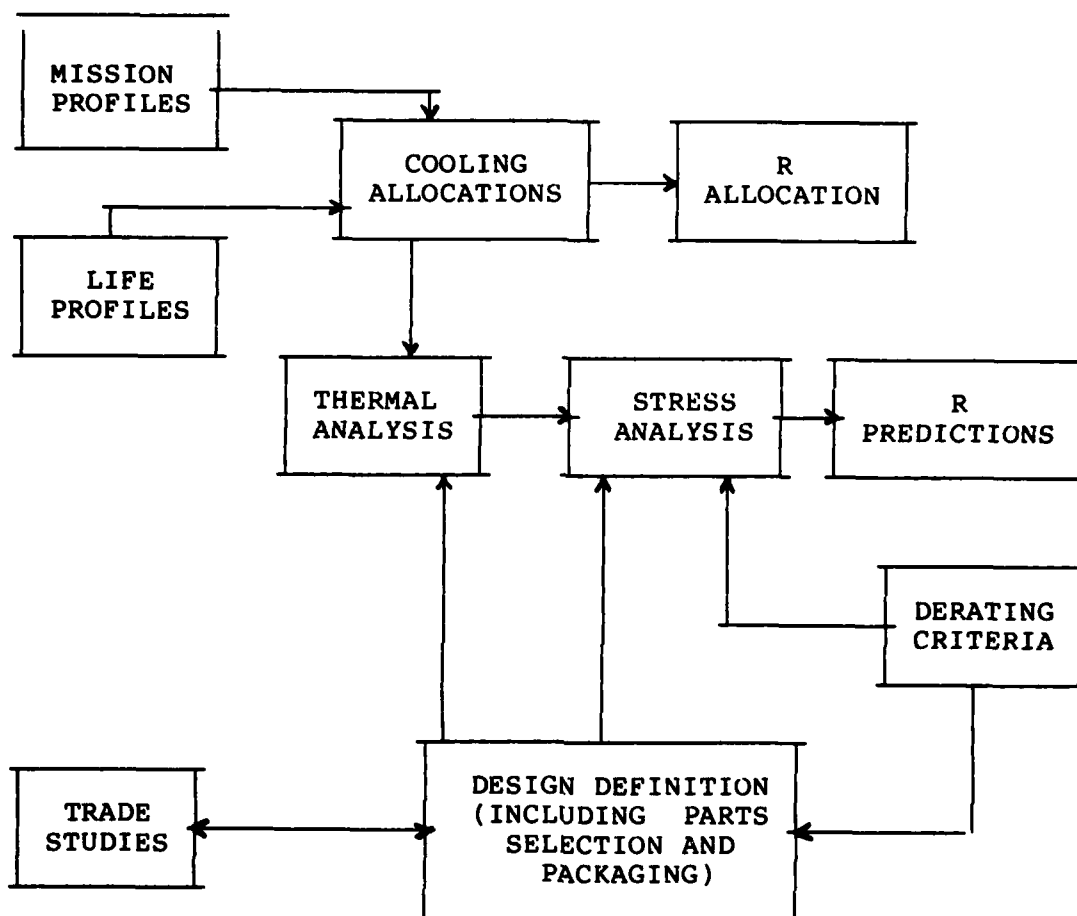


FIGURE B-21. R-Related Activities  
in Electronics Design Interrelationships

In general, the findings from the case studies have indicated an acceptable scheduling of efforts. Figure B-19 shows an overall sequence for the major activities.

An area where schedule dependencies is very important is during the test and evaluation phase. In the case of the F-18, the reliability development tests were run concurrently with the total aircraft full-scale development tests. The same generation of hardware was tested in both programs. Some additional problems were identified in the development test, but had it been run earlier in the program, the full-scale testing could then have been done on the next generation hardware, thus giving feedback on the corrective actions found and implemented during development testing and identifying problems on the next generation of hardware prior to delivery to the fleet. Corrective actions found during the concurrent testing were not incorporated until later deliveries. Indications from these later deliveries show the APG-65 to have a field reliability approaching 40 hours versus the 24 hours reflected in the case studies. Had the development test been run earlier, this improvement would have shown up during the full-scale development test and on the first units delivered, but the fact of test concurrency allowed the systems to be fielded earlier than with sequential testing.

Also, in considering the preceding illustration (Fig. B-21), if the mission and life profiles are not defined adequately prior to the need for thermal analysis, the thermal analysis must either be delayed or begun using assumptions about available cooling capability. If the thermal analysis is delayed, the other efforts, including design iterations, must either be delayed or begun using assumptions.

If the dependent work is begun or completed prior to the independent work which feeds the system, the amount of difficulty later encountered is a function of the accuracy of the



assumptions made. If some of the assumptions are significantly in error, management is faced with a redesign effort, accepting the consequences or something in-between. Many times the cost and schedule consequences of redesign would probably be unacceptable. Therefore, something is done which produces less than the desired results. Additionally, the work done out of sequence uses the available resources ineffectively. An example of this is the failure modes, effects, critically analysis (FMECA). When this is done off-line after PDR, it is unlikely to significantly affect design for diagnostics or the elimination of single-point failures.

Ideally, a program should be structured such that needed information is timely and available. In practice, despite proper initial scheduling, information flow will sometimes break down and decisionmakers will have to decide the course of action to be taken based on limited facts. There is no set formula. Each decision should be made on its own merit. However, the decisionmaker should always strive to understand the risks; the decisionmaker should explore the schedule dependencies prior to making a decision.

## D. CONCURRENCY AND SCHEDULING

### 1. Introduction

This discussion on concurrency is limited only to those aspects relative to R&M. The degree of concurrency in a development program can introduce both positive and negative factors. These factors must be recognized by program managers and appropriate management action taken to structure a program that balances any increased risk with compensating program activities or resources.

Concurrency can be a positive factor in design maturation by resulting in earlier, more abundant failure data under the operational environment. One negative factor can be the reduced time that is available to take any design action after a design analysis or test before the design is frozen for production. In first generation technologies such as electrooptic systems it appears that the impacts may be more difficult to balance or may compound the risks associated with these technologies. In general the radars examined by the case studies represented second or third generation technologies with moderate concurrency and were able to compensate for the risks and show improvements over the previous generations. The risks being introduced by concurrency must be understood and balanced. To achieve this balance, detailed planning and risk assessment is a mandatory function. Readily available and well-planned options must be prepared for execution in the event concurrent activities clash and create program disruptions. As discussed in Section 2, Appendix F, the impact of a funding profile to provide a more advanced system prior to the start of testing will reduce some of the inherent shortcomings of test concurrency.

## 2. Definition

The defining of concurrency is not a simple matter. The Defense Science Board performed a study on concurrency in 1977. From that study, the following definition was developed:

"The conduct of the steps leading to production for inventory before the end of full-scale development time span."

The most frequent definitions found in literature on the subject included: (a) parallel (back-up) technological development, (b) concurrent, but independent subsystem development and testing, (c) co-production, and (d) overlap of dependent, normally sequential activities.

## 3. Concerns of Concurrency

Use of the concurrency concept on a program has both advantages and disadvantages which must be weighed against all other program functions. If the risks warrant use of concurrent actions, then it is reasonable to limit the advantages/disadvantages as follows:

- Potential advantages include: (a) concurrency potentially allows the attainment of an earlier IOC, (b) increased likelihood of meeting intermediate goals and thresholds, (c) lower overhead costs, (d) work force continuity, and (e) increased worker motivation.
- Potential disadvantages include: (a) concurrency may lead to premature commitment to high-cost program elements, (b) excessive and high-cost changes in design after production has commenced, (c) less reliable equipment in service, and (d) degradation of training because of multiple configurations and faulty systems.

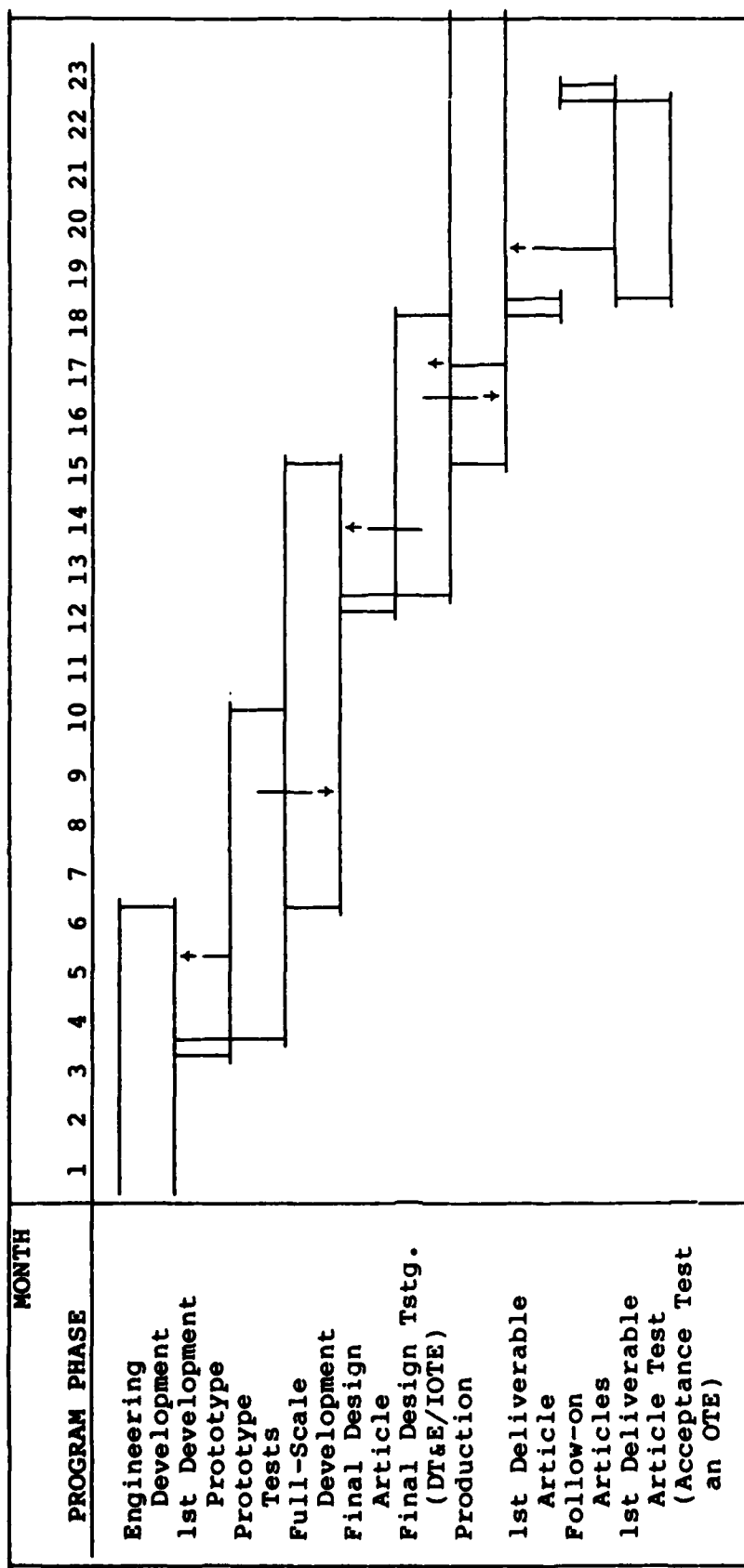


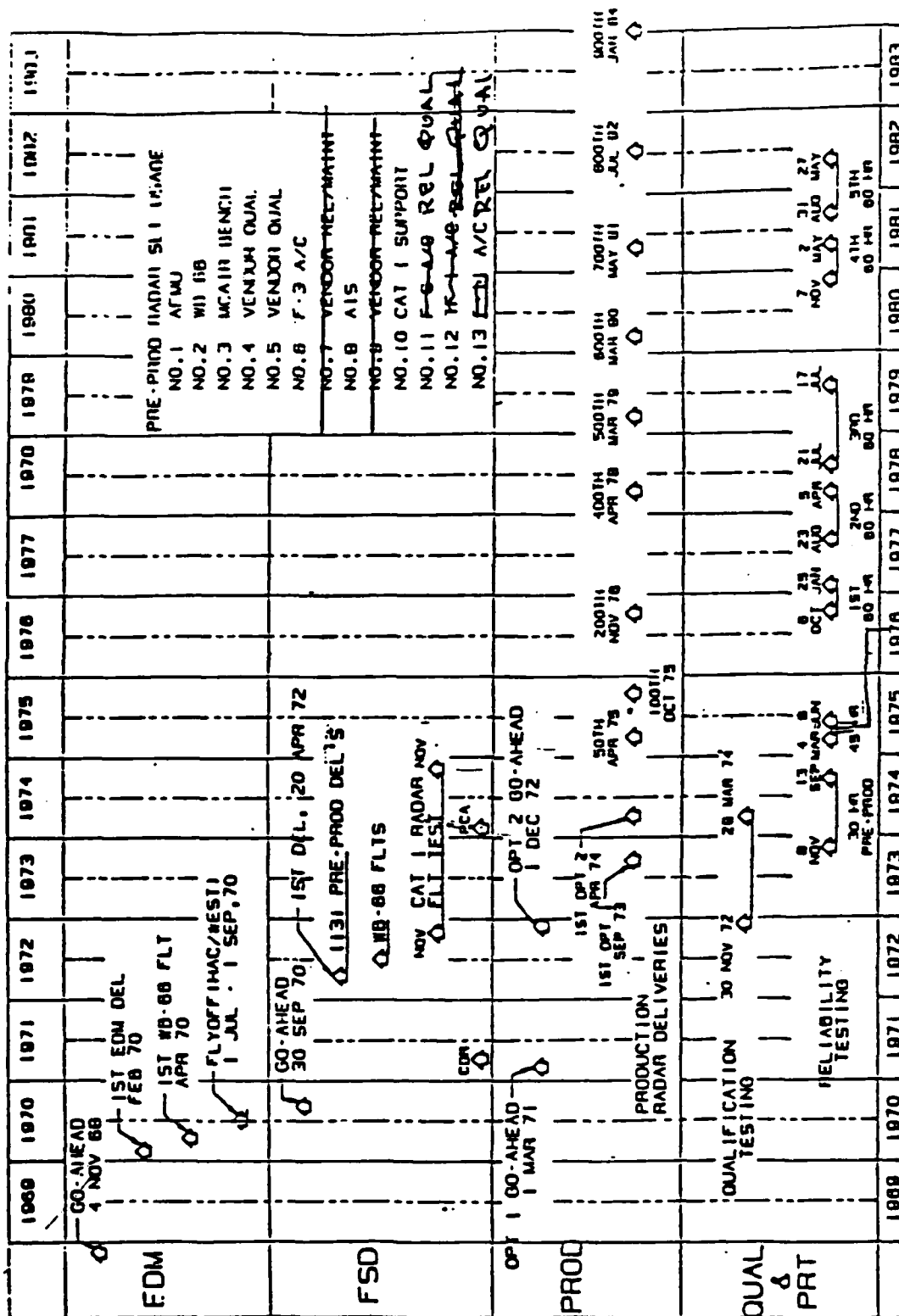
FIGURE B-22. Hypothetical Concurrency Schedule

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The effect of concurrency on R&M factors in a program can be very positive, assuming the available data are applied correctly. The benefits gained result from the insight to problems through feedback from one action to another, i.e., prototype testing to full-scale development during design. The feedback concept is illustrated in Fig. B-22. The provision for continuing feedback to design, production procedures, parts screening or evaluation, etc., allows R&M factors to be reviewed and evaluated in a very near real-time fashion. As a result, changes can be determined and effected sooner to make improvements where required and avoid problems at a later time in the program's development.

The case studies performed on the F-15/16/18 radar systems demonstrated how concurrent activities played a role in producing systems with significantly better R&M factors than previous generations.

The overlap of various program phases all appeared to contribute to the development of a better level of R&M (see Figs. B-23, B-24, B-25 and B-26). Obviously, planning and management awareness were very important factors in achieving these gains. It is also interesting to note that the concurrent activities did not coexist with production for a prolonged period of time.



**FIGURE B-23. F-15 Radar Historical Events**

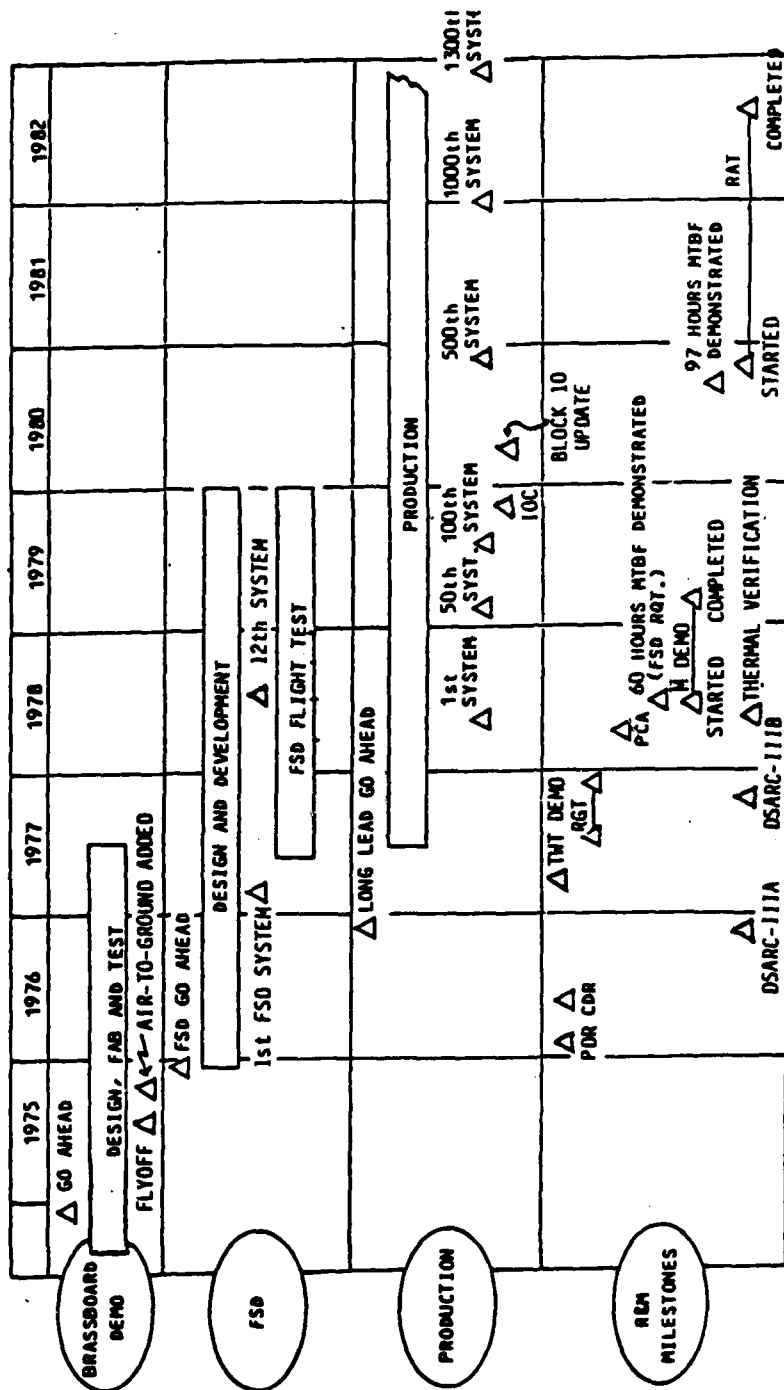


FIGURE B-24. F-16 APG-66 Program Summary

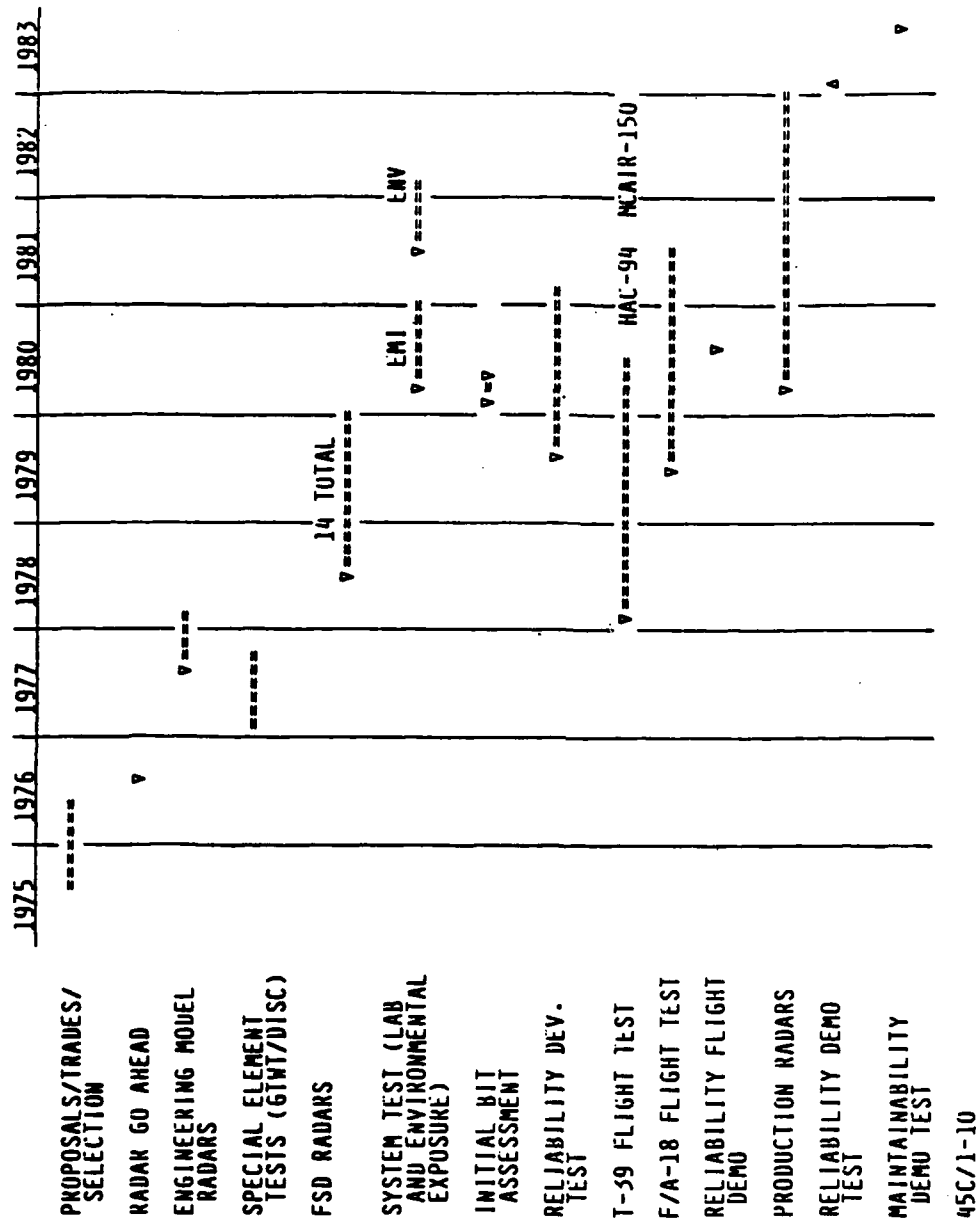


FIGURE B-25. F-18 Program Elements





#### 4. Scheduling Factors

The sequencing and time allocated for accomplishing the tasks associated with the key R&M elements are critical if the R&M requirements are to be met when production hardware is delivered to the user. Many of the R&M elements are interrelated and should be properly scheduled to design, develop and build reliable and maintainable systems.

There are many items that must be considered when developing a concurrent program schedule, some of which may result in less than an optimum schedule for R&M considerations. The key items that influence concurrent program schedule decisions are budget constraints, urgency for system, system complexity and technology being used. Scheduling considerations for the various R&M elements will be discussed in subsequent paragraphs of this section. The impact that budget/time constraints can have on developing successful, from an R&M viewpoint, systems is also discussed along with R&M schedule considerations when introducing new/advanced technology. It is assumed, in subsequent paragraphs, that there are three phases in the program(s)--concept definition/validation, full-scale development, and production.

a. Concept Definition and Full-Scale Development. As indicated above, there are usually three phases of the system acquisition process. R&M element considerations start at the beginning of the process and continue into production as shown in Fig. B-27.

In general, the R&M requirements and design criteria elements should be established/implemented in the concept definition phase, and the R&M/design evaluation analysis and R&M testing in the FSD phase. A system for identification and investigation of problems should be used throughout the acquisition process. The acquisition period through FSD will vary from program to program.

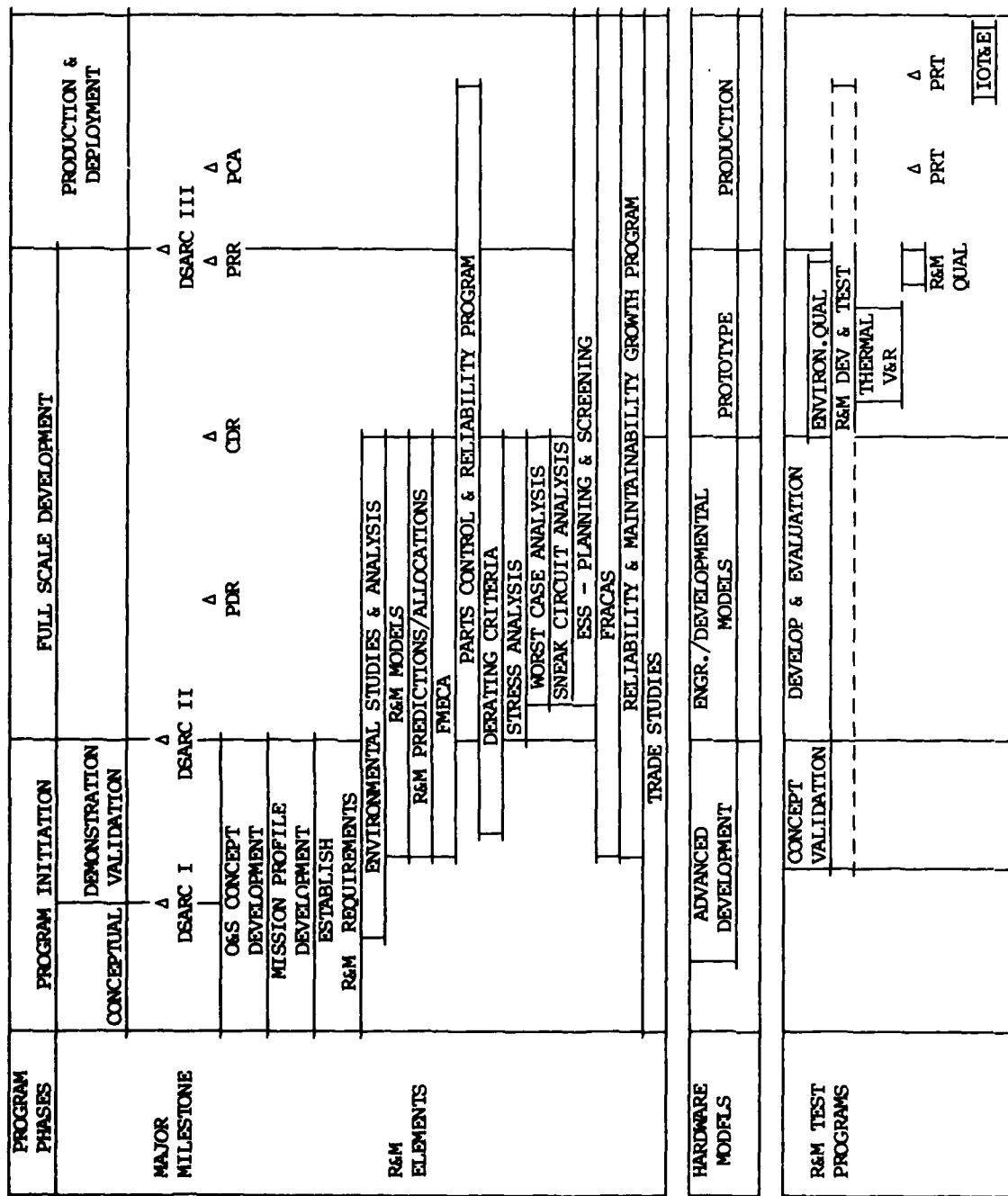


FIGURE B-27. R&M Acquisition Cycle

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The data presented in the case studies indicated a six- to seven-year cycle for the radars that were reviewed (see Fig. B-26) and ten years for the T700 engine (See Fig. B-28).

Failure to establish requirements and design criteria prior to start of detail design will stretch out the design period and/or may require redesign at a later date. It should be noted that even though work is started on these elements prior to FSD, it is necessary to continue and update the data throughout the design period.

(1). Scheduling of R&M/Design Evaluation Analysis.

Trade studies, update of R&M models, environmental studies/analysis, derating criteria and R&M predictions and allocations are continually performed throughout the detailed design period. The R&M design evaluation analysis (thermal analysis, stress analysis, FMEA, worst-case analysis and sneak-circuit analysis) must be an integral part of the detailed design process and continue to be updated through CDR and as required, when changes are implemented. These R&M design analyses need to be conducted concurrent with the detailed design so that the analysis results can cause design changes in a timely manner. While most of these analyses are normally associated with electric/electronic design, similar type analyses are applicable to and done for mechanical systems.

Scheduling of PDRs and CDRs are dependent on complexity of system, technology being used, extent of front-end design, development work planned and the urgency for the system. The period of time between start of FSD to CDR varied from four months for the F-16 radar to eleven months for the F-18 radar. Engineering models of the F-15 and F-16 had been designed, fabricated and tested during the concept definition (demonstration) phase of the program so a lot of the design tasks had been accomplished prior to the start of FSD. For design evolution systems such

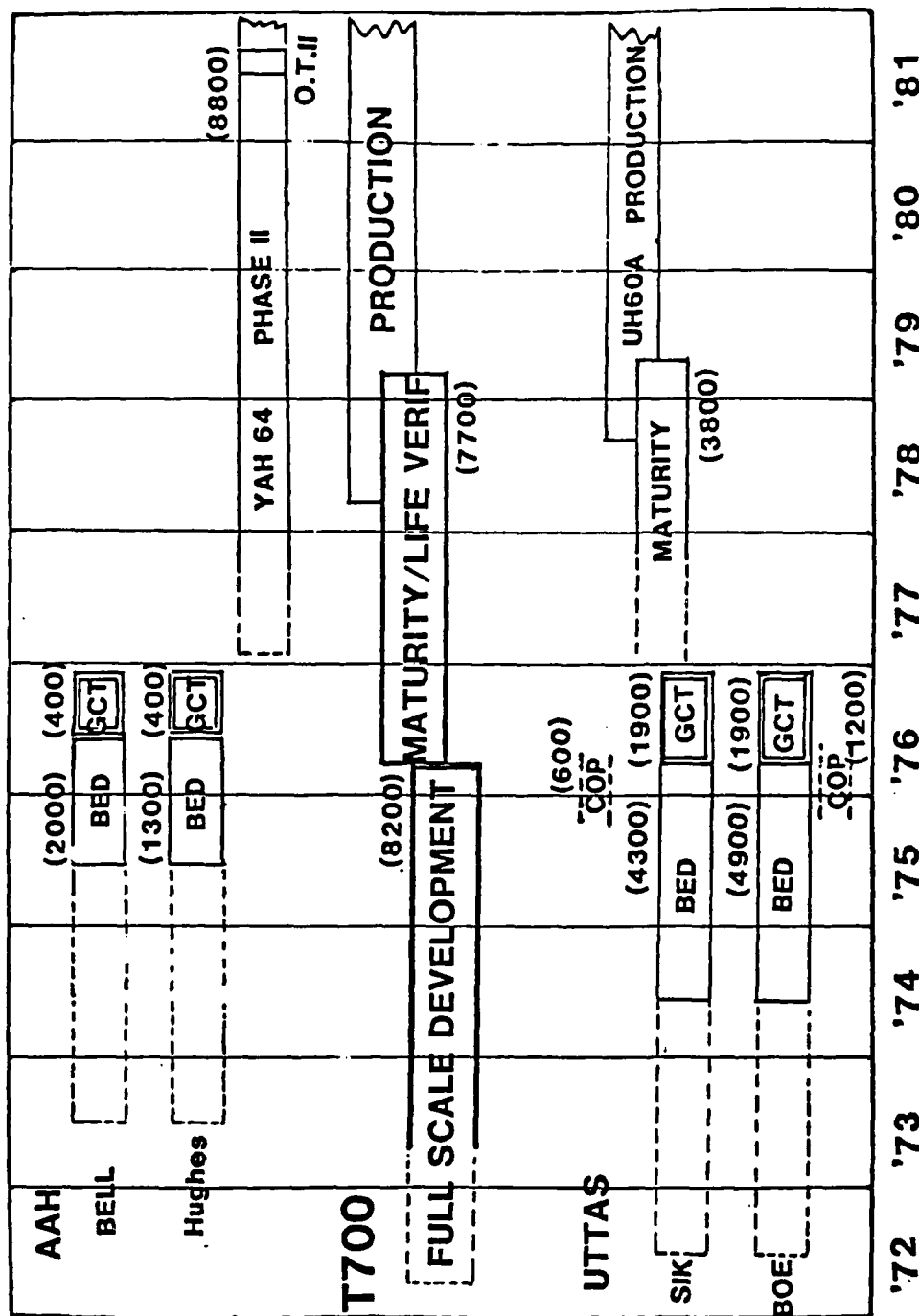


FIGURE B-28. T700 Blackhawk/Apache Development Program

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as the F-15, F-16, and F/A-18 radars about one year from FSD turn-on to CDR is adequate to accomplish the design task.

(2). Scheduling of Tests for R&M. Good front-end engineering for R&M is necessary for providing reliable and maintainable hardware to the user but there is no way all of the R&M problems can be anticipated and designed out. As the program transitions from engineering model hardware to prototype systems to production to the field, new environmental, skill, tooling, process and usage conditions are encountered that will identify/introduce new problems. At each of these points, testing and design changes are often required. The testing that is accomplished during the demonstration/validation phase and engineering development portion of the FSD is primarily for technical performance evaluation. The hardware used in these tests is usually engineering developmental models and not representative of the final design. The hardware fabricated during FSD is representative of the CDR design but usually is not fabricated with the controlled processes and tooling that will be used during production. The configuration of the production hardware will probably not be the same as the FSD hardware due to changes required as a result of the FSD testing.

Because of the evolution of the hardware configuration, the formal reliability and maintainability qualification tests or demonstrations should be scheduled late enough in FSD to assure that the configuration is as close as possible to the production configuration but early enough to provide for timely corrective action. Reliability development growth testing scheduled prior to demonstration testing can be used to identify corrective action or early FSD configurations and allow demonstration testing to be accomplished on later configurations with corrective action incorporated.

Data from all design, development and production tests should be used to determine design changes that will improve the reliability and maintainability of the hardware. Thus, the importance of feedback from concurrent actions comes into play.

(a). Failure Reporting, Analysis and Corrective Action (FRACAS). Reliability growth during the acquisition cycle is dependent on identifying and correcting problems. Identifying and correcting the problems as early in the cycle is desired to assure early incorporation of fixes. A failure reporting, analysis and corrective action system should be implemented during the concept definition phase and used for the complete acquisition cycle and during early field use. Here again, some degree of schedule overlap is important, and again concurrency becomes an element in management of the program.

(b). Reliability & Maintainability Growth Program. A well-planned R&M growth program is very effective in the development and production of a reliable system. The program should be structured to use data from development, integration, qualification, reliability qualification, production and operational tests. A reliability growth test with dedicated assets should be included in the reliability growth program. A reliability growth test would provide a lot of test hours in a controlled environment. This should be scheduled early in the FSD program so that any changes could be incorporated in production hardware. The duration of the growth tests should be determined by corrective actions generated instead of a fixed number of operating hours.

If dedicated assets for reliability growth testing are not available due to cost considerations, the growth testing could

be combined with the qualification tests. In fact, failure data from nearly all testing can be growth data if careful analysis is performed. The risk of relying only on data from other tests is that all of the design/operational envelope conditions may not be encountered early in the development program and some problems not detected until a later time period.

(c). Thermal Verification Tests. One important factor affecting reliability is good thermal management. In all of the case studies, a thermal analysis was performed during the design to optimize the design of the hardware and thermal verification test conducted to evaluate the design. These tests should be conducted as early as possible so that required changes may be implemented prior to production. Caution should be exercised to ensure that tests are not run until the system operational environment has been verified.

(d). R&M Qualification (Demonstration) Test. The problem of starting reliability and maintainability demonstration tests too early on unrepresentative configurations, versus too late on production equipment, presents a dilemma typical of all testing. Early testing involves additional risks of failing the required R&M test requirements versus later testing when the ability to incorporate early production fixes is minimized.

When development growth tests are specified, Reliability and Maintainability demonstration tests may be scheduled later in the FSD program to assure that the configuration is as close as possible to that of production hardware. When development growth tests are not specified, demonstration tests must be conducted early to provide for timely corrective action. Demonstration testing scheduled late in the FSD program without prior reliability development testing is of less value to the designer.



When many units are to be produced, but initial production rate is low, it may be acceptable to use the first production units for reliability demonstration if there has been an aggressive reliability growth program.

b. Production

When going from Full-Scale Development into production, the hardware faces a different environment, different people, different skill levels and different processes. To assure that Reliability has not been degraded with this transition, a production reliability test should be conducted early in the production cycle. To identify any degradation in reliability, production reliability tests should be done on a periodic basis.

The failure reporting, analysis and corrective action system developed during the development phase should be carried on into the production phase and used for production acceptance testing and production reliability program. The data obtained can be used for reliability growth during the production cycle.

BIT/BITE should be used to the maximum extent possible during production testing. FRACAS data obtained in this manner can be used to improve system maintainability. The F-16 program has been very successful in achieving reliability growth during production.

By employing a reasonable level of concurrent activities between production and FSD, the feedback will allow timely corrections to be made that will reduce degradation to the R&M factors of the system.

(1). Impact of Concurrency. As shown in Fig. B-26, the F-15, F-16, and F/A-18 programs were highly concurrent in that production go-ahead was before FSD completion. On the F-15, production go-ahead was one month after CDR and 14 months

before the first prototype system was completed. On the F-16 and F/A-18 programs, production go-ahead was approximately one year after CDR, and on the F-18 program before the first prototype system was completed. The first production radars were delivered approximately 1-1/2 years before FSD completion. The AN/TPQ-37 (FIREFINDER) ground-based radar went from Advanced Development phase to production.

The T-700 Turbine Engine program was the classic non-concurrent type program. The T-700 program structure included a 4-year (approx.) Advanced Turbine Engine Demonstration Program, followed by a 4-year FSD program. Production go-ahead was after completion of FSD. The FSD phase was followed by a post qualification maturity program. The maturity program resulted in a smooth transition to production and a significant reduction in design changes during the early years in the field.

The data from the above case studies indicate that concurrency did not have an appreciable impact on FSD schedules. The data does indicate, as one would expect, that all the R&M problems were not identified prior to delivery of production hardware, and it was necessary to incorporate retrofit changes in delivered hardware to meet R&M requirements.

It is believed that R&M requirements can be achieved at an earlier date in a concurrent program than in a non-concurrent program if the program is structured properly. Good front-end engineering and growth programs are required to achieve reliable and maintainable hardware. The funding profile proposed earlier in this report will help this. However, as discussed in previous sections, new problems are encountered when the program transitions from design to production and when it is first used by the operational forces. Since these events occur at an earlier date on a concurrent program, the problems identified after transitions are found earlier. To realize R&M improvements the program has to be structured for an R&M growth program extending into production and

early field deployment. Contractor engineering support in the field would be required for operational problems, understanding, feedback, and correction. To realize R&M improvements in a timely fashion the flow time for approval of Class I changes needs to be improved. The reliability growth experienced on the F-16 and TPQ-36 and TPQ-37 radar during production and operational deployment is an example of such a reliability growth program.

(2). Observations Related to Concurrency. In summary, for concurrent programs several factors must be accounted for and specific functions completed by management.

A program with concurrency applied must be well-planned. The funding profile for the total program must include earlier commitment of funds to provide a more mature design prior to the testing phase. Alternate paths must be identified early to assist in avoiding delays should problems arise due to the level of concurrency employed or for any other reason. Schedules must be laid out and maintained in order to ensure the necessary milestones are met.

Prior to implementation of concurrency in a program, all related risks must be reviewed and assessed. R&M benefits are just two of the many factors, and should by no means be the only driver.

The testing data and how they will be fed into the design, production and evaluation activities must be thoroughly understood and articulated to all levels of management. Checks and balances must be employed to be sure concurrency is providing the desired results.

## 5. Analyzing Program Schedule

One of the first steps in the acquisition of new systems is the process of selecting an acquisition strategy and establishing the program schedule. The strategy selected will depend on a variety of factors in order to take into account when the system is needed (i.e., the threat), the capability of existing systems, political considerations, cost, technological maturity, etc. The program schedule is then developed considering those factors. Numerous Service and independent agency studies have addressed this process. One of the more recent of these studies, the Air Force's "Affordable Acquisition Approach (A<sup>3</sup>) Study" focused heavily on this front-end part of the acquisition process and highlighted the importance of realistic program baselines--getting off on the right foot. The question is how can we do it?

The purpose of this section is to present a prototype tool for analyzing program schedules. This tool, and others to be developed, used in conjunction with existing tools such as "should cost analysis" can be evolved into a set of expert judgment aids to improve the baselining process.

Tools and analytical approaches are required in order to: (1) develop acquisition program plans which establish attainable program baselines, i.e., a reasonable balance of design time, environmental testing, field maturation, funding levels, etc., (2) provide a reasonable capability to access program factors during the front-end process as well as throughout the development process as program contingencies force changes to the baseline plan. An example of such a tool and an analytic approach has been developed for airborne fire control radars which if refined and tested can be used as a pattern for other types of systems. The fire control radar example was developed using information from the case studies for the APG-63 (F-15), APG-65 (F/A-18),

and the APG-66 (F-16), information from the Air Force maintenance data system (DO-56) and a study for the Air Force by General Electric. The GE study, "Research Study of Radar Reliability and its Impact on Life Cycle Costs," provides information for the APQ-113 (F-111A and F-111E), APQ-114 (FB-111A), APO-144 (F-111F) and the APQ-120 (F-4E). Table B-1 presents the data used to discuss the example.

The concept, using the fire control radar as an example, establishes a standard way of presenting information on a class of like systems so that "red flags" could be raised on new systems when certain parameters are identified. That is, historical information on a similar class of radars may be used to highlight areas for further investigation. Figure B-29 represents one such approach. In this example, the number of electrical parts in each radar is plotted versus the number of months from contract go-ahead to the delivery of the first production unit. The number of parts is used as a surrogate for complexity because it tends to be a measure which equates the magnitude of the design and engineering task between systems and because it tends to do so regardless of the technology used in the system. For example, the APG-65 and the APQ-120 contain about the same number of parts but are, from a technology view point, very different, e.g., 172 integrated circuits (ICs) in the APQ-120 versus 5,329 ICs in the APG-65. The APG-65, developed ten years after the APQ-120, is also a far more capable radar. Even so, the task of integrating 13,500 parts into a working radar can be assumed to be equivalent for our purposes.

The second variable plotted on Fig. B-29 is the number of months from contract go-ahead to delivery of the first production radar. Intuitively, it should require incrementally more time to develop and deliver a radar as complexity (number of parts) increases. The next step was to draw a line to represent the relationship of complexity to time, i.e., as the number of parts

TABLE B-1. Airborne Fire Control Radars--Summary Data

RADAR	AIRCRAFT	# ELEC PARTS	# ICS	WT LBS	VOL FT <sup>3</sup>	MONTHS GO AHEAD TO PRODUCTION DELIVERY					# PARTS/ # MONTHS/ 1000
						# 1	# 100	# 200	# 400	# 600	
APQ-113	F-111A/E	10704	1081	370	6.90	36	56	63			.297333
APQ-114	FB-111A	11160	1094			17	40				.656470
APQ-144	F-111F	11545	1081	370	6.90	9	30				1.282778
APQ-120	F-4E	13553	172	637		12	19	21	26	36	1.129417
APG-63	F-15	18830	7157	516	8.99	30	60	66	86	98	.627666
APG-65	F/A-18	13467	5329	344	3.60	25	52				.538680
APG-66	F-16	9500	4039	296	4.37	12	29	32	38	43	.791666

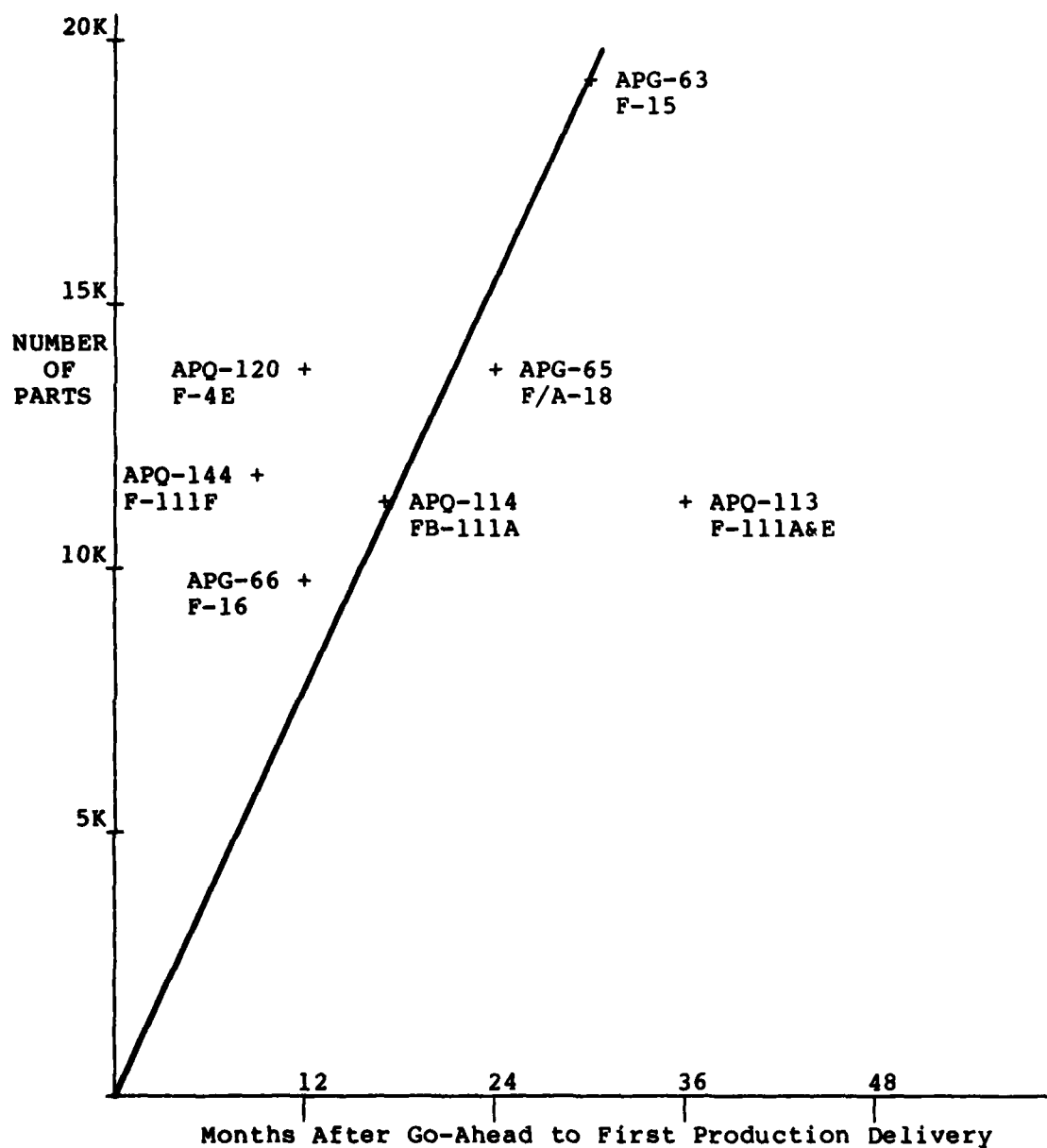


FIGURE B-29. Airborne Fire Control Radar Development--Number of Months from Go-Ahead to First Production Delivery

increases, how much additional development time is required.

Before proceeding, it is important to understand what this analysis can and cannot be expected to do. The purpose of the tool and the supporting analysis process is not to judge a program schedule as good or bad but instead to judge the balance between time and complexity when other program factors and development techniques are reviewed for reasonableness. Table B-2 is a matrix for comparison of the factors used in conjunction with Fig. B-29 to develop the prototype analysis approach. With an understanding of what the tool can be expected to do and with a detailed knowledge of the radars, gained from the documents referenced above and recent data from Service data systems, the three most recent radars were selected to construct the reference line. The judgment to use these three radars was made because they are considered to be successful developments with a reasonable balance of R&M factors and because they were essentially new designs. In order to make the tool more useful throughout the range of potential applications, the line was forced through the origin (0,0). The resulting reference line is shown on Fig. B-29. The next step tests the utility of the chart. Again, the purpose of this tool is to raise "red flags" when further investigation is warranted.

The remaining four radars (with Table B-2 as a reference) were used to test the utility of the approach. The APQ-113 radar for the F-111A and F-111E falls considerably to the right of the reference line. That is, if the line represents a reasonable amount of time from go-ahead to the first production delivery for a given complexity (parts count), the APQ-113 exceeds the time roughly by a factor of two (36 months actual versus 17 months using the reference line). The GE study, along with historical trends in fire control radar development provides



TABLE B-2. Characterizing R&M Treatment in Fire Control Radar Programs

	DESIGN NEW (N) OR EVOLVED (E)	DESIGN ITERATION DURING DEVELOPMENT	HIGH RATE DELIVERY SCHEDULE	PROGRAM SIZE (# OF UNITS)	LEVEL OF R&M STRESS	ENVIRON TESTING EFFORT	FIELD MATURATION PROGRAM	RELATIVE FIELD RESULTS
APQ-113	N	Y	N/A	SM	HI	HI	LO	MED
APQ-114	E	N	N/A	SM	HI	MED	LO	MED
APQ-144	E	N	N/A	SM	HI	MED	LO	MED
APQ-120	N	N	Y	LG	LO	LO	LO	POOR
APG-63	N	Y	N	LG	MED/HI	MED	LO	GOOD
APG-65	N	Y	N	LG	HI	HI	MED*	GOOD*
APG-66	N	Y	Y	LG	HI	HI	HI	GOOD/EXCEL

\*NOTE: APG-65 radar is still in the early fielding process; thus, final results are not known.

insight which indicates that the reference line is useful for our intended purpose. The APQ-113 program was a watershed program in many ways: (1) its design was among the first to depend heavily on solid-state components (new technology), (2) the program had a very strong reliability requirement that was enforced, (3) many new/evolving design, parts selection and parts screening techniques were used (e.g., 1,413 hours of ROT, 7,000 hours of RAT, 89 percent high reliability parts selected, a very detailed design integration to reduce parts count, etc.). The combination of these factors indicates that the APQ-113 was first to do many things--a learning process for the Air Force and the contractor. Although the time to first production article appears excessive (compared to the reference line) a great deal was learned from the program which has been refined and used in all radar development programs since.

If a new program was being reviewed today and it fell in the same area of the chart as the APQ-113, one would want to know why (e.g., is new technology being applied?, are new untried design approaches being used?, etc.). If the potential benefits were judged to be worth the extra time (i.e., watershed for future developments), the program could be approved or other alternatives like off-line maturing could be explored.

The next two radars used to test the approach are the APQ-114 and APQ-144. Both of these radars are direct derivatives of the APQ-113 as shown in Fig. B-30. Considering the concurrency of the APQ-114 and APQ-113 programs and the cross-flow into the APQ-144 program, the 113 & 144 points tend to add validity to the proposed review approach.

Finally, the APQ-120 program was used to test the validity of the approach. The APQ-120 program is a good case history of a fast track (need it as soon as possible) program. The radar was needed to meet Southeast Asia needs. It was developed quickly without substantial design iteration and virtually none of the

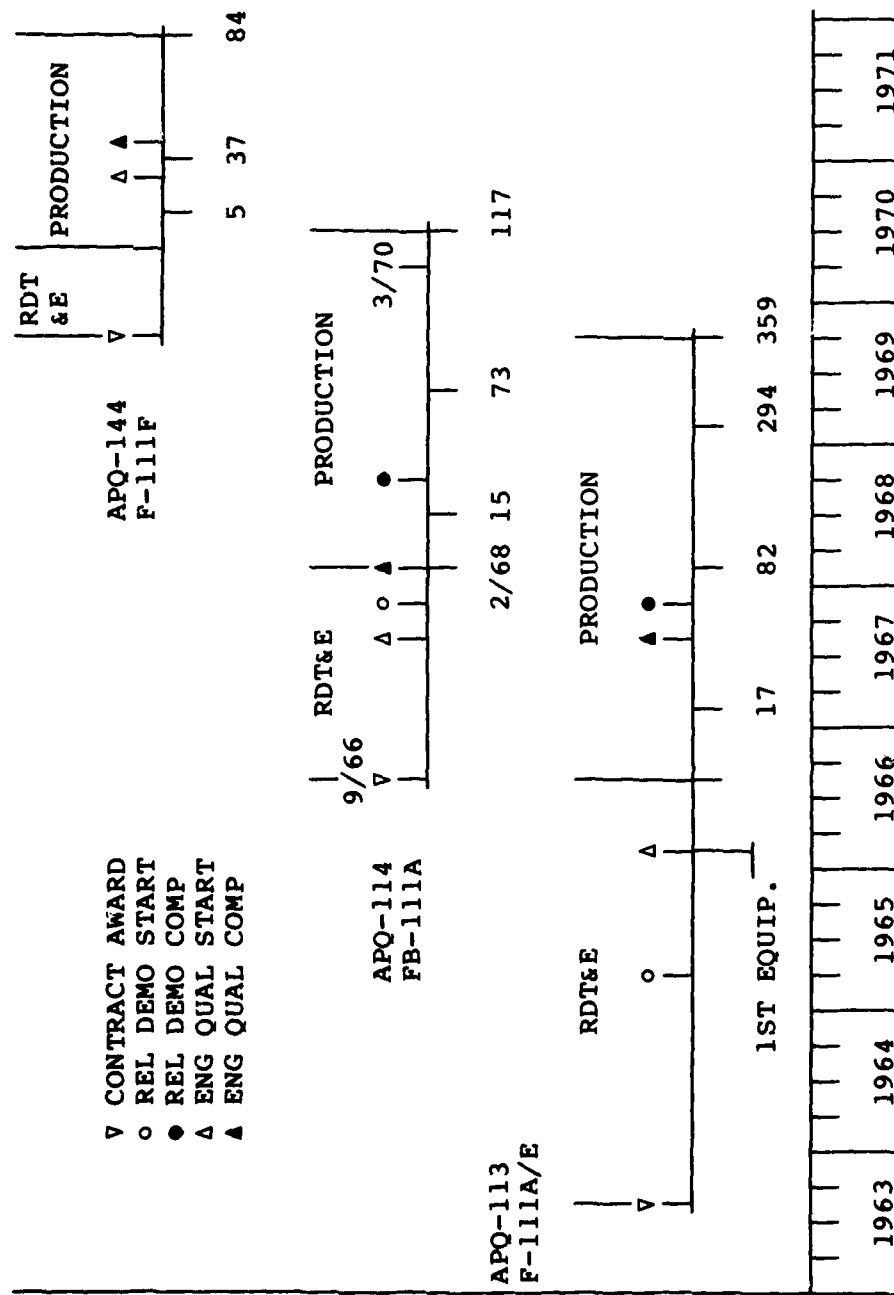


FIGURE B-30. Design Inheritance, APQ-113

testing and parts selection techniques used for the APQ-113, and the three new radars used to construct the reference line in Fig. B-29. It was also produced at a very high rate, as shown on Fig. B-31. (The lower the line on Fig. B-31, the faster the rate of production.) In the APQ-120 program, 600 units were delivered in 36 months. As might have been predicted from the reference line and other known information on the treatment of R&M, the APQ-120 has suffered from its heritage with low reliability, and has had very little opportunity to grow its reliability short of a total redesign.

The tool discussed above is not a substitute for a program structuring process where knowledgeable contractor, Service acquisition specialists and user personnel interact to develop a balanced acquisition plan. In fact, as discussed above, the three programs used to construct the reference line were selected because they were balanced. That is, they contained a reasonable mixture of proven techniques that are known to enhance R&M characteristics. Some of those techniques are listed in Table B-3. A more detailed discussion of this approach is contained in Appendix B and in the Navy "New Look Approach."

TABLE B-3. Front-End Task/Techniques for R&M

- |   |
|---|
| <ul style="list-style-type: none"><li>● REASONABLE YET CHALLENGING R&amp;M REQUIREMENTS</li><li>● PLANNED DESIGN ITERATION</li><li>● PARTS SELECTION PROGRAM</li><li>● ENVIRONMENTAL TESTING (RDT, RAT, ETC.)</li><li>● OPERATIONAL TESTING</li><li>● ENVIRONMENTAL STRESS SCREENING</li><li>● PLANNED MATURATION PROGRAM</li></ul> |
|---|

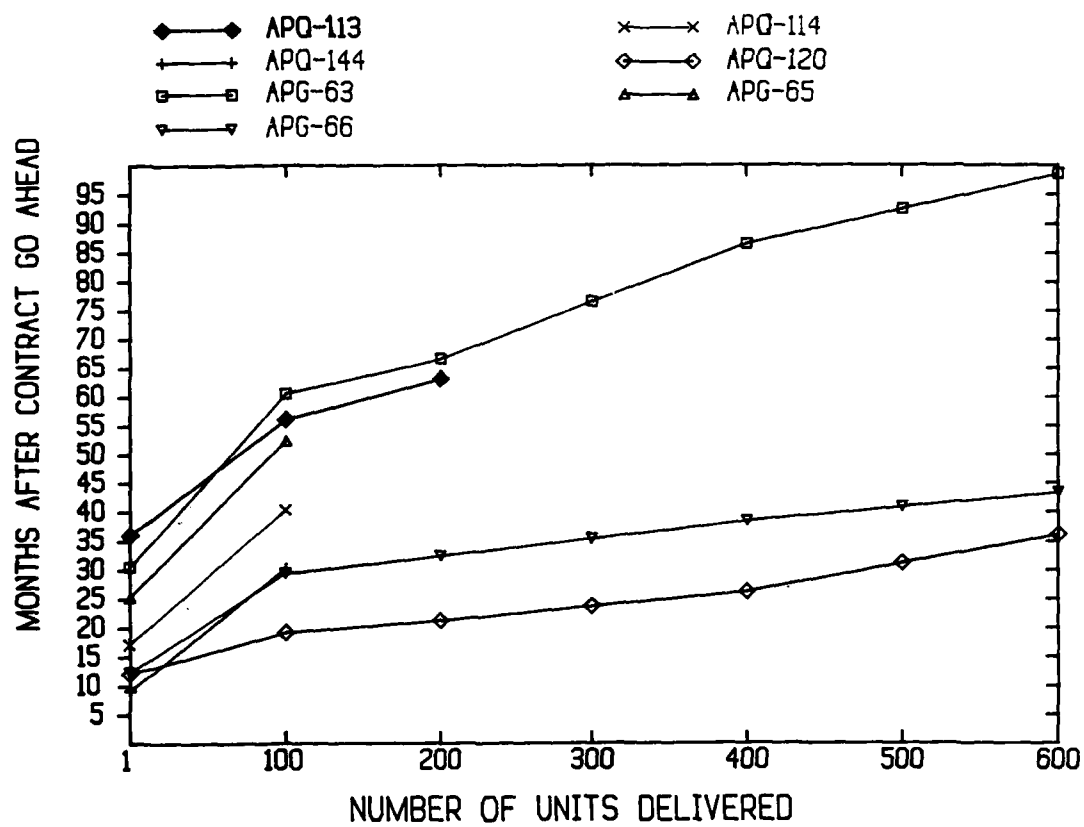


FIGURE B-31. Radar Delivery Schedule Comparison

APPENDIX C

ELECTRONIC WEAPON SYSTEMS ANALYSIS

## APPENDIX C

### ELECTRONIC WEAPON SYSTEMS ANALYSIS

This Appendix discusses the analysis of the structuring and execution of reliability and maintainability programs as observed across electronic weapon systems programs reviewed. It also considered other information that was presented or obtained during the course of the study. Observations and analyses contained in this section are primarily based on the review of the radar case study reports for the F-15 (APG-63), F-16 (APG-66), F/A-18 (APG-65), FIREFINDER (TPQ-36/37), Lightweight Doppler Navigation System (APN-128) and AEGIS radar (AN/SPY-1A). These radar developments cover a total time period of about 15 years and represent the best efforts of all three services, i.e., Army: FIREFINDER, Navy: AEGIS and F/A-18 radars, Air Force: F-15 and F-16 radars. The purpose, performance, and complexity vary widely for the systems (in terms of complexity the number of component parts involved range from less than 5,000 parts to over 500,000 parts).

For this analysis, the R&M program activities were divided into five major categories: contracting, management, design, manufacturing, and test and evaluation. These five categories were divided further into 26 elements. A Program Review Document, developed in this study, was used to provide a mutual understanding of the 26 elements and to communicate the scope and content of the elements to personnel in the government program offices and contractors involved in the individual acquisition programs that were examined.

As a result the observations and findings associated with these electronic programs are considered valid for future programs for complex electronic systems. To a lesser extent, these results may also be appropriate for newer generation developments such as electrooptical systems but no effort has been taken to verify that claim.

## A. CONTRACTING

This section addresses the seven contracting elements identified and defined in IDA Record Document D-26, R&M Program Review Elements.

### 1. R&M Requirements

The procuring activities for each of the radars appeared to appreciate the necessity for firm R&M contract requirements with some form of verification. They avoided the procedure used a number of years ago where "goals" were specified and R&M did not receive proper attention. R&M values were stated in slightly different ways and varied as lessons were learned from previous contracts. Mean-time-between-failures (MTBF), based on radar operating time, is used as a contractual measure of hardware reliability, whereas mean-flight-hours-between-failures (MFHBF) is used to reflect service operational reliability performance. Although the definition of "reliability" in most military standards (MIL-STD-721, for example) includes a "probability of success," this is seldom used any more since it is difficult to measure. Maintainability, however, is different in that probabilities or percentages are useful to describe fault isolation/BIT characteristics (i.e., 95 percent fault detection). Maintainability sometimes uses time and percentages to describe requirements (e.g., 120 minutes max for 90 percent of all maintenance actions). Mean-time-to-repair (MTTR) and maintenance man-hours/flight hour (MMH/FH) are widely used in specifying and measuring maintainability.

Although the methods used by the Services to define R&M requirements were substantially different, each method worked and each program has been successful. Methods used reflected the popular notions at the time the request for proposal (RFP) was being prepared. Figure C-1 summarizes the salient R&M requirements associated with the radar cases studied:



	<u>F-15</u>	<u>F-16</u>	<u>F/A-18</u>	<u>FIREFINDER</u>	<u>AEGIS</u>	<u>LDNS</u>
MTBF(HRS) (1)	30-60	60-97	50-106	90-150	135	1000
TWT(MTBF)	2000	3000			N/A	N/A
MMH/FH	-	0.5	0.26 (4)	N/A	15.2/day	N/A
MTTR(HRS)	0.77	0.5	0.20 (3)	0.5/2.0	2	.25 (0) .50 (I) 1.00 (D)
FAULT-DETECTION	95%	95%	98%	75-98%	100%	
FAULT-ISOLATION	95%	95%	99%	90%	95%	
FALSE ALARM	2%	<1%	<1%	(2)	-	
RIW	No	Yes	No	-	NO	YES
INCENTIVE AWARD	No	\$K	\$M	\$K	YES	YES

(1) MIL-STD-781B test hours

(2) Confidential value

(3) O-Level only

(4) O- and I-Level

FIGURE C-1. R&M Requirements Summarized

a. R&M Contract Goals versus Requirements

It is widely recognized today that when R&M contract requirements are specified as goals instead of verifiable requirements, they do not receive proper attention by the contractor. When R&M values were specified as goals, as was the procedure a number of years ago, technical performance received a higher priority in the minds of management. Engineers tended to design their equipment to pass the test section of a specification. Goals without a verification test received a low priority in the design process. Not only must R&M be stated as a requirement, but verification tests need to be identified and growth expectation specified. Each of the six radar cases studied contained firm R&M requirements with preplanned verification tests which provided for growth. In one case, the FIREFINDER (AN/TPQ-36), MTBF "goals" of 400 hours (four times as high as the required 100-hour MTBF) were also included in the contract (Ref. FIREFINDER Case Study, IDA Record Document D-24, p. 9). Experience would indicate that the 400-hour goal value will not be an effective method of obtaining improved equipment R&M. Similarly, the F-15 RFP initially required a 100-hour avionic subsystem MTBF with a goal (objective) of 150 hours (Ref. F-15 Case Study, IDA Record Document D-19, p. IIA-7).

The FIREFINDER case study provides a good example of Goals versus Requirements. The TPQ-37 Advanced Development Contract contained only a 250-hour MTBF Goal and it appears that the contractor placed the major emphasis on performance (Ref. FIREFINDER Case Study, p. 58). When the TPQ-37 system went from Advanced Development to Low Rate Initial Production (LRIP), a firm 90-hour MTBF requirement was added to the contract, along with an incentivized Reliability Demonstration Test. The measured MTBF went from 33 hours for Advanced Development configuration to 115 hours for the LRIP radars. Many things contributed to the Reliability improvement; however, it is believed that the management emphasis placed on meeting the Reliability requirements during the incentivized demonstration test was a major factor.

b. Developing R&M Requirements

Properly defined, realistic, but challenging R&M requirements are fundamental to successful R&M development. Program R&M requirements establish the basis for determining resource needs and the R&M approach during design, development and production. The successful cases studied emphasized the word "realistic." An unrealistically high requirement can result in excessive program costs and program disruptions when the figure cannot be met. Too low a requirement may result in too little R&M emphasis and the loss of an opportunity to get significantly higher R&M at essentially no increase in acquisition cost.

Program R&M requirements should ensure that the program produces a system/equipment which is operationally adequate and logistically supportable. Contract requirements need not be specified in operational terminology, but they must be selected such that achievement of the contract requirements ensures that the operational and logistics support requirements will be met.

Many of the successful cases studied followed the foregoing defined approach. In the F-16 radar case, comparability studies were done using operational data factored for improvements expected from technology and better design. Operational experience of previous radar systems was compared to MIL-STD-781 test results of the same systems to determine what the contractual test requirements should be to provide a high probability of achieving the projected field performance. Significantly, the F-16 radar has surpassed field projections.

Realistic yet challenging R&M requirements can be defined using analytical techniques and past operational experience. Analytical techniques are available to establish the relationships between R&M and operational impacts, and logistics supportability. Operational experience is available to establish baselines which can be useful in developing rational engineering projections of what can be realistically achieved.

c. Testability Requirements

The establishment of testability requirements, particularly in the area of built-in-test, has evolved slowly over the past fifteen years. Most programs have followed the lead of their predecessors and have made only small changes and improvements in capability. There have been very large increases in computer power (currently 210K 16-Bit words for the F/A-18) with advanced revisions of the F-15 growing to 8.2 megabits total capacity. This should mean better fault isolation where LRUs or modules can be redesigned to capitalize on the increased memory, especially in digital circuits. The ability of BIT to detect and isolate failures varies with the type of LRU/SRA and module with analog processors and receivers being more difficult than digital or signal processors. Fault detection requirements indicate some increase in the level of detection from 95 percent for the F-15, and 95 percent for the F-16 to 98 percent for the F/A-18.

AEGIS is indicating 100 percent fault detection coverage, monitoring operability test, and a periodic test. For the FIRE-FINDER, the requirements are:

- Fault Isolation and Repair on Site
  - Organizational - 90 percent of repairable faults
  - Direct support - 10 percent of repairable faults
- Automatic Fault Isolation (BIT) to:
  - 1 unit for 75 percent of failures
  - 2 units or less for 90 percent of failures
  - 8 units or less for 98 percent of failures

(Ref. FIREFINDER Case Study, p. 61).

## 2. Mission Profiles

Mission profile development should begin in the earliest program phase and continue to some degree throughout the program. If mission profiles are not defined early in the program, then critical design decisions may not consider the expected operational stresses. Each of the programs studied approached the derivation and use of mission profiles in different ways, being influenced by the practices in use at the time and by the Military Service involved. The following is a summary:

- In the 1970 time period when the F-15 program was initiated, there was an emphasis on the Point Intercept Mission and making the F-15 an Air Superiority Fighter (Ref. F-15 Case Study, p. IA-2). Modifications for other mission capabilities that added cost, weight, or complications were not allowed. The byword was "not a pound for air-to ground" capabilities. At one time, it was planned to fly a number of dedicated point intercept missions to demonstrate R&M, but this idea was later dropped. After a review of the various F-15 missions, it was decided that Test Plan III, Level F of MIL-STD-781B would be used as the basis of reliability demonstration tests. Test Level F called for testing from -54°C to +71°C with sine vibration between 20 and 60 Hz with 2.2 g's  $\pm$  10% peak acceleration. During initial design, it was found that additional hardware (heaters, control circuits, etc.) would be required for consistent repeated turn-on at -54°C (Ref. F-15 Case Study, p. IC-4). The test condition was modified to radar turn-on at -40°C following stabilization at -54°C in the off mode (Ref. FIREFINDER Case Study, p. IIE-19).

- In 1973, when the FIREFINDER program was initiated by the Army, the environmental requirements for weapon-locating radars were well-defined and the mission profiles established. The mission profile for the TPQ-36 was: (a) operational time 10 days at 24 hrs/day, (b) Travel and Maintenance mode 21 hrs/day, (c) emplacement/displacements 3 hrs/day (d) scheduled and unscheduled maintenance time 1 hr/day. The system had to operate under worldwide environments per Army Regulation 70-38 (up to 125°F ambient conditions) in addition to rain, and transportation over rough terrain (Ref. FIREFINDER Case Study, p. 65).
- By 1974, when the F-16 radar procurement was initiated, it was recognized that the ten minutes of sine vibration at 2.2 g's peak acceleration was effective mostly as a means to dislodge loose solder. Random vibration appeared more representative of mission conditions. As a result, reliability tests were conducted with random vibration at 2.96 g's RMS between 20 and 2000 Hz. Level F was specified with -40°C turn-on (similar to the F-15).
- In 1976, when the F/A-18 program was initiated, the Navy's "new look" program emphasized the importance of mission profile definition in all areas of design and test endeavors. An Operational Mission Environment (OME) was derived, based on the frequency of occurrence for each mission established for Navy Fighter, Navy Light Attack, and Marine Fighter/Attack Squadrons, as well as ship/shore and combat/training sortie ratios. The resulting OME formed the basis

for establishing expected flight load, vibration, temperature, altitude, humidity, acoustic, salt, and dust conditions. The OME concept permeated and influenced thinking in all design areas (Ref. F-18 Case Study, p. 70-71). Since the Reliability Development (TAAF) tests were established long before the OME was completely developed, these tests were a mixture of different test philosophies. Test Level F (-54° stabilization, -40°C turn-on and operation up to +71°C) and various vibration exposures were used. These were: (a) 12.6 g's RMS at 50 to 2000 Hz for non-gunfire simulation, (b) 21.6 g's RMS for endurance, (c) 37.2 g's RMS at 500 to 2000 Hz for gunfire, (d) sine vibration at 0.2 to 4.6 g's in the 5 to 50 Hz range for non-gunfire, and (e) 10 to 18 g's in the 50 to 500 Hz range for gunfire.

### 3. Life Profiles

Detail design actions must also address the stresses that are projected for the system's life profile. The non-mission portion of a system's life can include design requirements that are not contained in the defined mission profile. None of the case studies specifically addressed this subject but it is known that each program had requirements to provide for storage, packaging, transportation and handling effects on the radar equipment.

The following is a case history from the F-15 that may be representative of most programs. Considerable effort has been expended by Hughes to provide insulated shipping containers for transporting radar LRUs from Hughes in Los Angeles to MCAIR in St. Louis and other worldwide destinations. These containers appeared satisfactory for several years. In 1978 MCAIR started observing damage to the outer perimeter ring of antennas and thought that they were causing this on aircraft installation. Further investigation and test revealed that the antenna attaching clamps were not securely holding the antenna during shipment. Redesign to the interior of the shipping package solved the problem. As an added precaution, accelerometers were installed in each type of radar LRU shipping container to ascertain if the shock during shipment could cause damage to the LRUs.

### 4. R&M Failure Definition

R&M requirements have complete meaning only if established in a defined context. Variations of failure definition, time, critical failures, etc., result in wide variations in the meaning of R&M parameters and inadequate communication between government and contractors. Agreements and definitions must be in writing and established at an appropriate point in the contract.



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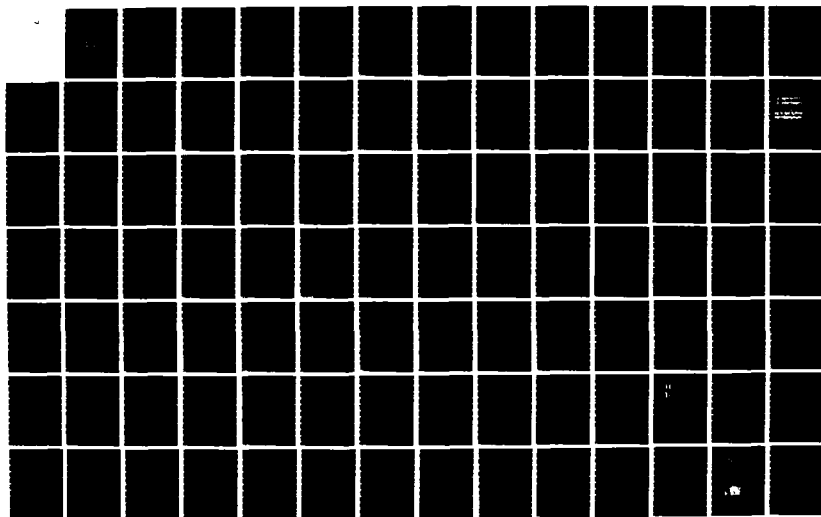
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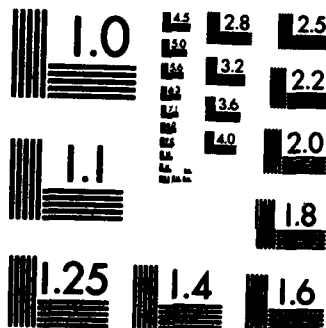
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MICROCOPY RESOLUTION TEST CHART  
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The hardware attribute commonly referred to as "reliability" is generally recognized as one of several contributors to the frequency of field maintenance. Other external contributors include adequacy of test equipment, manuals, training, and the attitude and skill levels of equipment operators and repair personnel. There is a tendency for users to compare frequency of maintenance to inherent "reliability," be unhappy with the results, and blame failure definitions and ground rules.

The three airplane radar contracts, F-15, F-16, and F/A-18 were conducted under MIL-STD-781B, "Reliability Tests: Exponential Distribution," which in paragraph 5.5.1 defines failure categories (Ref. F-15 Case Study, p. II A-3; F/A-18, p. 77).

According to the standard, all failures are relevant and chargeable unless and until determined to be non-relevant or non-chargeable, or both, by the procuring activity. As a rule, contractors collect failure data, analyze the occurrence and propose a relevant or non-relevant classification. The burden of proof is the contractor's responsibility. The final judgment is rendered by the procuring activities. Failure category definitions are expanded upon in Reliability Test Plans, which are required to be submitted after contract go-ahead. Procuring activities and contractors generally concurred in the following:

- Installation damage, mishandling, test equipment failures are non-relevant.
- Secondary CFE failures are non-chargeable if a primary (causative) CFE or GFE failure has been charged.
- Pattern failures require corrective action.

In the F/A-18, a ground rule used during FSD included provisions for classifying a failure as non-relevant if a fix had been identified prior to the field occurrence. (This approach was a compromise between counting all failure occurrences until the fix was implemented and not counting repeats of known problems, (Ref. F/A-18 Case Study, p. 76). One contractor believes that this

method projects a realistic trend as to what can be expected in a mature system in the field. This is definitely somewhat optimistic for early field results but will be closer after early support problems are resolved. Another position is that adjustment of demonstration test results on the basis of corrective actions not yet incorporated is an appropriate procedure, given an adequate understanding of the failure event and the effectiveness of the associated corrective action. Based on AMSAA Technical Report 375, June 1982, and a presentation by Dr. Larry Crow, U.S. Army Materiel System Analysis Activity, Army experience indicates that this procedure is optimistic and generates projected values which on an average overestimate system reliability.

The FIREFINDER failure definitions are:

- Relevant Failure (chargeable)
  - Reduces System Performance below Specified Levels
  - Caused by Design or Manufacturing Defects or Physical Deterioration
- Non-Relevant Failure (Non-Chargeable)
  - Damage from Improper Installation, Mishandling, or Abuse
  - Failure due to Error in Test Procedures
  - Failure due to Externally Induced Overstress
  - Operator Errors
  - Secondary Failures
  - Failure of GFE Items
  - Redundant Items

(Ref. FIREFINDER p. 69).

Since the AEGIS System design involved the concept of multiple redundancies in all principal functions and can accept certain malfunctions/failures as long as acceptable performance is maintained, their failure definitions are different from those of an airborne radar. AEGIS definitions are listed in the following, with Fig. C-2 depicting graphically performance profile characteristics.

(a). Major/Critical Events

- Events that reduce performance below specified thresholds
- Restoration is manual and completed in minutes or hours
- Based on 72-hour mission profile.

(b). Interrupt Events

- Events that temporarily reduce performance below specified thresholds
- Restoration is automatic and completed in seconds
- Based on 72-hour mission profile.

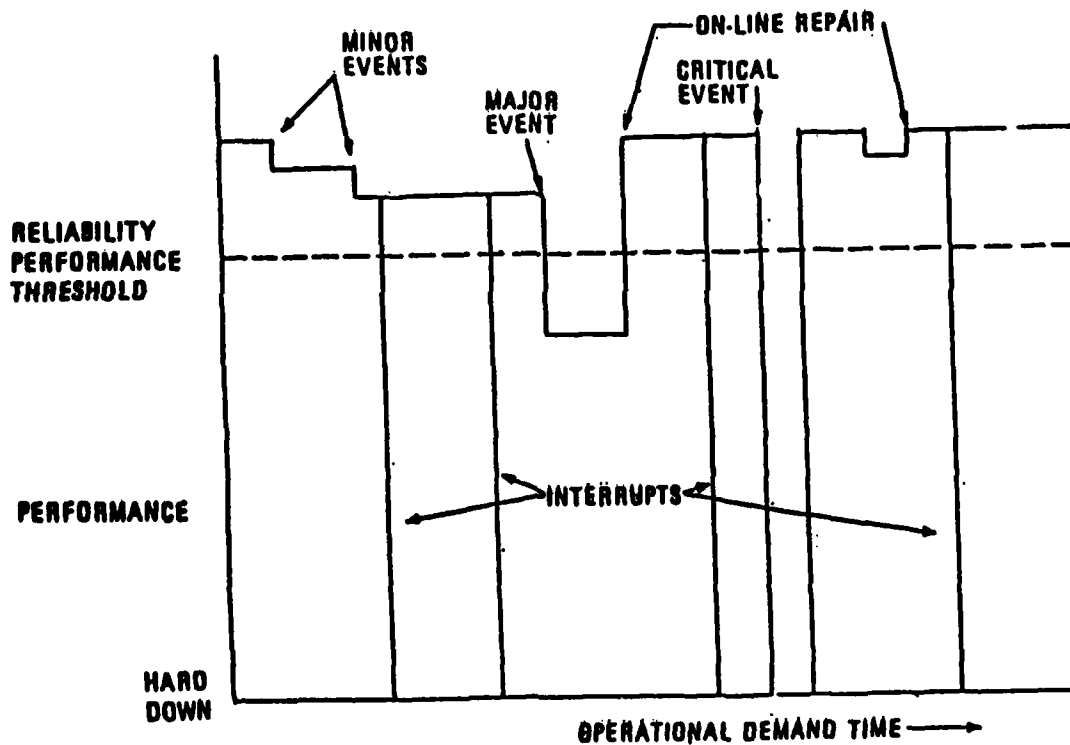


FIGURE C-2. AEGIS Performance Profile Characteristics

## 5. Incentives

R&M contract incentives can aid in developing reliable and maintainable systems by focusing contractor management attention on actions that improve and ultimately meet specified requirements. The F-16, F/A-18, and LDNS programs contained incentives that were successfully implemented to the contractor's and the government's benefit.

The RIW (Reliability Improvement Warranty) played an important role in two programs. These were:

(1). Lightweight Doppler Navigation System (LDNS): the contractor warranted that the LDNS units furnished were free of defects in material, workmanship and design, and would operate in the intended environment for the specified warranty period. The contract provides for renewal of the warranty.

Any unit that failed to meet the warranty and was returned to the contractor was to be repaired or replaced at the contractor's sole option and expense. The contractor is not obligated to perform cosmetic repairs. Repaired or replaced items were to be tested against a specified Acceptance Test Procedure. The government witnessed test activity and reviewed the documented results.

For purposes of the warranty, the Initial Anniversary Date (IAD) was the date of successful completion of DT III PVT-G (Production Validation Testing-Government) Testing. This date was used to establish reporting and adjustment periods for the warranty.

For all Low Rate Initial Production units, the initial warranty period started when the government accepted a unit and extended 48 months after the IAD. The contractor and contracting officer negotiated the price for any renewal of the warranty period.

The contractor does not pay for repair/replacement of units for nonconformance, loss or damage due to:

- (1) Non-LDNS induced fire or explosion
- (2) Submersion
- (3) Aircraft crash

- (4) Enemy action.
- (5) Natural disaster, or
- (6) Accidental or willful mistreatment.

The exclusions did not apply at contractor-controlled locations, or if the LDNS caused one or more of the above events. Clear and convincing evidence was to accompany the contractor's claim from relief from Warranty Obligation for any of the above listed exclusions.

The contractor was to repair or replace any defective unit in accordance with the terms of the warranty. The Contractor was not liable for special or consequential damages (Ref. LDNS, IDA Record Document D-23 pp. 65/2-3, 4).

Additional cost to the government for the RIW provision is priced with each batch of units shipped. These costs generally represent between 10 and 15 percent of the procurement cost.

(2) F-16 Radar System: In an attempt to motivate the contractor further after he won the contract award in 1974, the Air Force included in the contract an option to exercise RIW provisions. In 1977, a contract was subsequently signed with GD for RIW coverage of five (out of seven) radar LRUs for the U.S. and the European Participating Governments (EPG) in the Multinational Fighter Program. The warranty applied to all units installed in the first 250 USAF and the first 192 EPG production aircraft and to spares procured for support of those aircraft.

The LRUs selected were:

- Transmitter
- Signal Processor
- Computer
- Receiver
- Antenna.

The radar control panel and rack, cable and waveguide assembly LRUs were excluded from RIW. Figure C-3 lists the major features of the RIW program.

90/8-2

Characteristic	Description
Units covered	Five different radar LRUs
Aircraft	250 USAF and 192 European F-16As and F-16Bs
Coverage period	Four years or 300,000 flying hours (whichever occurs first)
Contract time	Prior to full-scale production
Air Force Logistics Manager	Ogden Air Logistics Center (ALC)
Participating countries	United States, Belgium, Denmark, Norway, and The Netherlands
Contractor	General Dynamics (prime)
Price	Range from 2% to 6% per year of LRU cost
Contract price adjustment for flight hours short-fall	Applicable if flying hours are less than 250,000 in 4 years
Turnaround-time requirement	22-days average (Depot)
Fault isolation at base	Yes

FIGURE C-3. Major Features of the F-16 Radar RIW Contract

89/25-2



Incentive award fees were effectively utilized on two programs. These were:

(1) F/A-18 Radar Program: As part of the Navy's "New Look" in R&M, an incentive award fee was issued as part of the basic contract to provide MCAIR an opportunity to gain awards based on demonstrated aircraft performance in the areas of R&M. These award fees were then structured to allow major suppliers to participate in the Navy's "New Look" R&M incentive.

The reliability features of the radar to be demonstrated were MTBF and MFHBF. The maintainability features were MMH/FH (O-Level Unscheduled), DMMH/FH (O&I Total) and MFHBMA (O-Level). These requirements were selected to be demonstrated during the production reliability test, the 1200FH, 2500FH, and 9000FH periods. The incentive award fee was structured to provide 60 percent of the total award pool to reliability and 40 percent to maintainability (Ref. F/A-18 Case Study, p. 78).

Financial incentives were provided contractually in the F/A-18 radar program as shown in Fig. C-4.

(2) FIREFINDER Radar Program: The Reliability Improvement Program (RIP) for the TPQ-37 created an incentive in dollars for the contractor to exceed a 90-hr MTBF during a government-funded demonstration. The value of the incentive was \$5.5 million, less the cost of the RIP. The objective was to achieve 17 or fewer failures in 1500 hours of testing. The cost of the RIP was \$4.8 million. Thirteen failures were experienced and the contractor earned approximately 90 percent of the incentive or \$508K. The incentive schedule was as follows:

<u>FAILURES IN 1500 HOURS</u>	<u>\$ INCENTIVE</u>	<u>ACTUAL</u>
12 or less	565K	-
13	508K	X
14	452K	-
15	396K	-
16	339K	-
17	283K	-

(Ref. FIREFINDER Case Study, p. 73).

F/A-18 APG-65 RADAR

R&M INCENTIVE AWARD FEE STRUCTURE

- MAXIMUM AWARD = 5% OF FSD PURCHASE ORDER COST
- WEIGHT CONSTRAINTS ON RELIABILITY AWARDS
- QUALITATIVE LIFE CYCLE COST CONSTRAINT ON MAINTAINABILITY AWARDS

	R&M PARAMETERS	MAXIMUM AVAILABLE AWARD FEE AS PERCENT OF R&M AWARD POOL			
		Prod Rel Test (781B)	1200 FH	2500 FH	9000 FH
R 60%	MTBF	30	9	--	--
	MFHBF	--	-	21	--
M 40%	MMH/FH (O-lev, Uns)	--	4	6	--
	DMMH/FH (O&I, TOT)	--	-	8	12
	MFHBMA (O-LEVEL)	--	-	4	6
	TOTAL	30	13	39	18

(Ref. F/A-18 Case Study, p. 80).

FIGURE C-4. F/A-18 Radar Program Incentives

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#### 6. Source Selection Criteria

In a recent LMI review of 20 major weapon systems programs, it was evident that government source selection criteria had not consistently placed adequate priority on R&M (Fig. C-5).

	<u>TOTAL NUMBER OF PROGRAMS REVIEWED</u>	<u>NUMBER WITH R&amp;M IN SOURCE SELECTION</u>	<u>PERCENT</u>
ARMY	6	2	33%
NAVY	6	0	0%
AIR FORCE	<u>8</u>	<u>4</u>	<u>50%</u>
TOTAL	20	6	30%

(LMI Working Note: "A Documentation of DoD Strategies for Acquiring Weapon System Reliability and Support" Dec. 1982 pp. 2-2, 2-3, and 2-4)

FIGURE C-5. R&M is not Consistently Used in Source Selection

Programs reviewed in the LMI study consisted of 6 Army programs, 6 Navy Programs, and 8 Air Force programs. Army programs included the M-1 Tank, Patriot Air Defense, Bradley M2/M3 Infantry Fighting Vehicle, Apache AH-64 Helicopter, Blackhawk UH-6A Utility Tactical Transport, and DIVAD Air Defense Systems. Navy systems consisted of the F/A-18 Fighter Attack Aircraft, Tomahawk Submarine Launched Cruise Missile, F-14A First-Line Fighter, S-3A Viking Anti-Submarine Warfare Aircraft, MK-86 Gun Fire Control System, AEGIS Shipboard Air Defense and Phalanx Close-In Weapon System.

Air Force Programs were the B-1B Bomber, NGT Trainer, KC-10 Tanker, A-10 Close Support Fighter, F-16 Lightweight Fighter, ALCM Air-Launched Cruise Missile, AWACS Airborne Warning and Control,

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and GPS NAVSTAR Global Positioning System. Of the weapon systems reviewed by LMI, individual case studies were done for the F-16 Radar, the F/A-18 Radar, and the Blackhawk T700 engine.

As reported in the T700 case study, the inclusion of Reliability and Maintainability in the Source Selection criteria left no doubt that the Army was serious about R&M Requirements (Ref. T700 Case Study, p. IIA-75). Likewise, the F-16 Radar case study shows that Reliability and Maintainability were key factors in the RFP (Ref. F-16 Radar, p. IIA-14).

Although the LMI study reported that R&M was not used in source selection for the F/A-18 program, the individual case study for the F/A-18 Radar reported that the importance of R&M in source selection for the radar was clearly established through briefings, request for proposal instructions and hard specification requirements. In addition, R&M evaluation was conducted in all key proposal areas including Design, Manufacturing/Production Plan, Management and contractual, not just in the R&M proposal volumes (Ref. F/A-18 Radar Case Study, p. 87).

From the case studies analyzed, it is evident that when the hardware procurers placed heavy emphasis on R&M in the source selection process, then the contractors and suppliers in turn reflected that relative importance.

## 7. Life-Cycle Cost Considerations

A system's life-cycle cost is a function of R&M variables and can be reduced by selecting and achieving certain R&M requirements. During design trade studies, LCC was used as one factor to evaluate alternative designs. LCC efforts were similar among the contractors studied. Some examples are:

- a. F-15 - Life-Cycle Cost analyses were conducted in the initial design formulation studies and during trade study activities. Figure C-6, "BIT Mechanization Trade Study," lists costs as well as R&M and other factors considered (Ref. F-15 Case Study p. IIC-7). Throughout the development history of the radar (1972-1983) there were numerous changes. The ten representative VECP changes (see pp. IIC-9 through 21 of the F-15 Case Study Report) were LCC evaluated by Hughes and checked by MCAIR before incorporation into VECP and submittal to the Air Force.
- b. F-16 - Westinghouse conducted LCC analyses and submitted them to General Dynamics and the Air Force using cost models specifically designed to measure LCC. A major concern in the APG-66 radar development program, relative to LCC, was the TWT. Problems identified on earlier radar programs led to this concern. As a result, separate tests were required for the TWT. (Ref: F-16 Case Study p. IIA-16.)
- c. F/A-18 - MCAIR purchase orders to Hughes contained the life-cycle cost structure and design-to-cost structure so that both organizations participated in the analysis. Early in the program, MCAIR set-up an "off-line" team of people to monitor these analyses and to assure proper

MECHANIZATION CONSIDERATION	1. SHARED USE OF TACTICAL COCKPIT DISPLAY		2. CENTRALIZED DISPLAY OF - LATCHING FAULT INDICATORS (WHEEL WELL)		2. LATCHING FAULT INDICATOR ON EACH LRU		4. COMPUTER- CONTROLLED ALPHANUMERIC BIT PAPER TAPE PRINTER (WHEEL WELL)		5. RF DATA LINK TO TRANSMIT FAULT DATA TO GROUND STATION	
	COMMENTS	SCORE	COMMENTS	SCORE	COMMENTS	SCORE	COMMENTS	SCORE	COMMENTS	SCORE
1. PERMANENCE OF READOUT	BAD - Readout lost when power not applied or when CCC is removed	2	GOOD - Readout held until man- ually reset. Can become separated from faulty LRU	0	EXCELLENT - Readout held until manually reset after replacement of faulty LRU	10	GOOD - Tape can become separated from aircraft or faulty LRU	0	FAIR - Readout is likely to become separated from faulty LRU	0
Maximum Score: 10										
2. COST, WEIGHT, AND SIZE	EXCELLENT - Display already provided for other functions	10	GOOD - 7 lb + wiring, \$2 K unit cost, 300 sq. in.	0	EXCELLENT - Incremental cost is weight, \$10 and 0.000 lb. per LRU	10	FAIR - Requires increased CCC storage, \$4.7 K, and 10 lb.	0	POOR - Requires sig- nal conditioning, computer storage, logic interface with data terminal & new data link messages	4
Maximum Score: 10										
3. RELIABILITY	EXCELLENT - No degradation, existing display	0	GOOD - Two con- nectors between LRU and indicator	4	EXCELLENT - High probability indicator is con- tained in LRU	0	FAIR - Tape unit is electro- mechanical device	3	POOR - Complex mechanization	2
Maximum Score: 0										
4. MAINTAINABILITY	EXCELLENT - No increase in maintenance actions	0	GOOD - Indicators showing failed LRU's must be manually reset after LRU replace- ment	4	EXCELLENT - LRU indicator reset as part of LRU upgrade	0	POOR - Tape reader must be loaded before and unloaded after each flight	2	FAIR - Additional functions to be maintained	3
Maximum Score: 0										
5. COMPUTER STORAGE REQUIREMENTS	EXCELLENT - Display storage already provided for other functions	20	EXCELLENT - No storage required	20	EXCELLENT - No storage required	20	FAIR - Approx- imately 800-32 bit computer words required	12	BAD - BIT data must be formatted and stored until transmission	0
Maximum Score: 20										
6. MAINTENANCE 'ACCESS	FAIR - Technician must provide external or APU power and view readout in cockpit	0	EXCELLENT - Display always vi- sible from ground level without opening doors	10	BAD - Technician must open door to view indica- tors	2	EXCELLENT - Tape printer always accessible	10	POOR - Technician must retrieve data from data link recorder prior to main- tenance on aircraft	4
Maximum Score: 10										
TOTAL SCORE: 00	SHARED TACTICAL DISPLAY	40	CENTRALIZED FAULT INDICATORS	04	FAULT INDICATOR ON EACH LRU	04	BIT TAPE PRINTER	41	RF DATA LINK	24

FIGURE C-6. BIT Mechanization Trade Study  
(Ref. F-15 Case Study, p. IIC-7)

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attention. Proposed changes to the radar receive LCC analyses via the line F/A-18 organization today.

- d. FIREFINDER - Design-to-unit-production-cost was one of the principal design objectives of the AN/TPQ-36 radar. A \$700,000 award fee was established for this purpose. The objective was achieved by rigorous examination of all production costs while simultaneously ensuring that the performance and R&M requirements would be met. These examinations were done not only at the hardware design and implementation level, but at earliest stages of conceptual design (Ref. FIREFINDER Case Study, p. 96).
  
- e. LDNS - A life-cycle cost analysis was conducted. The life-cycle cost was defined as R&D cost, plus acquisition costs, plus ten years of operating and maintenance costs. Design and maintenance trade-offs (RIW versus Organic) were considered in determining the minimum cost of this equipment over its 10-year life span. Usage of the equipment in all phases of the life profile was considered. Cost-quantity relationships and risk-uncertainty criteria were developed as part of the LCC analyses (Ref. LDNS Case Study, p. 24-25).

## B. MANAGEMENT

The contractor organizations involved in the case study systems varied considerably. Most followed a matrix management approach with the contractor R&M personnel selected from a functional organization.

Prime contractor R&M management in the F-15 program was headed up by an engineering chief who in turn reported to the Director of Engineering. As the program progressed through the various phases, the backgrounds of the respective R&M chiefs were complementary to the respective phases of the program. In the 1969 time frame (early in the program) the R&M chief's background was largely operations and systems analysis which complemented early program activities of trade studies, predictions, plans and their impacts on life-cycle costs. During the 1973 time period, an R&M chief with an avionics background complemented the integration of radar design and testing efforts including MIL-STD-781B activities. In the 1976 and later periods, a chief with a background in laboratory and flight testing complemented test activity integration including production reliability tests with the resultant product improvements in radar R&M (Ref. F-15 Case Study, p. IIB-10). Although this type of evolutionary R&M management history was not detailed in the other case study reports, it is presented here based only on F-15 data as it does serve to point out that as a program passes through various stages, areas of activity and focus do change and should be considered in selection of managers for the various functions in the various phases.



## 1. Planning, Control and Emphasis

In looking across successful R&M programs, one of the important questions was the role of planning and control in the R&M process and the emphasis placed on R&M. From these reviews, it is evident that the emphasis placed on R&M by the government in the entire program process from conception, RFP, source selection, FSD and production is probably the single most important driver to achieving reliable and maintainable weapon systems.

Ways of providing emphasis are discussed both in this section and under contracting (para. a). Once real emphasis on R&M was established by the government, the contractor top management reflected this emphasis, and a better balance was provided between R&M, cost, schedule and technical performance. Once emphasis was established, appropriate planning and control tools were activated and reasonable results were achieved.

This section provides some insight into the detailed analysis across several successful programs and approaches taken to emphasize R&M and plan and control the associated program process. High-level emphasis on R&M and a closed loop data feedback process were vital to the overall R&M success.

### a. Planning & Control

Program planning and control can influence the outcome of any event. Within the F-15 radar program, technical, cost and schedule requirements and controls were established between the prime contractor and the government and, in turn, passed on to suppliers through contract documentation.

Reliability and Maintainability program plans were required and control was exercised through formal review, data approval, and considerable personal contact between management and engineering personnel. R&M approval (signature) was required for release of procurement specifications, installations and assembly drawings, development test procedures and reports as

well as suppliers' data requirements (Ref. F-15 Case Study, pp. IIB-3 and IIB-9.)

Within the F-16 radar program, similar controls were enacted requiring R&M drawing signoff as well as participation in the configuration control board, failure review board and special corrective action teams. Of particular note was the special planning and control directed toward the potentially high-risk TWT development effort. (Ref. F-16 Case Study, pp. IIB-14 and IIB-18.) A key factor demonstrated here is the ability to identify and quantify potential high-risk items and subsequently plan and control the effort to substantially reduce risk.

For planning and control, the F/A-18 radar program used many concepts similar to those used on the F-15 and F-16 radar programs. To provide detailed visibility to the responsible managers, subsystem status charts were maintained which tracked performance, reliability, maintainability and cost factors. (Ref. F/A-18 Case Study, pp. 97 and 98.)

To provide additional R&M visibility and control, the F/A-18 radar program conducted R&M program review meetings which were attended by high-level government personnel. (Ref. F/A-18 Case Study, p. 94.)

Although the initial TPQ-37 program had difficulties with the implementation of a reliability improvement program in 1977, planning and control factors were initiated. The program included elements as seen in the other case studies such as program reviews and high-level failure review board activity. (Ref. FIREFINDER Case Study, p. 81.)

Across the programs analyzed, the quality assurance provisions were similar. Although mechanization varied from case to case, the objectives were essentially the same.

An important thread which stretched across the successful programs was the provision for timely data feedback which allowed early detection of problems and appropriate adjustments to the planning and control process to effect solutions.

b. Emphasis

Management emphasis was placed on R&M through a number of avenues across the programs analyzed. Reporting relationships and other related emphasis factors are discussed in the following paragraphs.

(1) Reporting Relationships

One of the methods of attempting to convey R&M emphasis in the past has been the elevation of the R&M function within the overall organizational hierarchy. Varying degrees of this are observable across the case studies conducted.

For the F-15 program, the prime contractor organization had the R&M chief reporting to the Director of Engineering. Their radar subcontractor had the R&M function reporting to the Radar Program Manager (Ref. F-15 Case Study, pp. III-B-10 and II-B-12).

For the F-16 program, which was an RIW contract, there was a somewhat different approach in that both the prime and subcontractor each had RIW program managers which reported to the vice-presidential level with matrixed interfaces to the Radar Program Manager who also reported to the vice-presidential level. In addition, the reliability function at the subcontractor reported through the Quality and Reliability Assurance Organization as opposed to the Director of Engineering as was the case on the F-15. (Ref. F-16 Case Study, pp. II-B-5 and II-B-7.)

Although organizational structuring was not provided in the F/A-18 and FIREFINDER case study documents, the AEGIS program does reflect another approach to organizational hierarchy. On the AEGIS program, the reliability function reported through the System Engineering function to the RCA AEGIS program management office.

Perhaps the whole question relative to the optimum placement of the Reliability and Maintainability functions was best related by a high corporate officer of a major California corporation in discussions at the corporation's first annual R&M symposium held toward the end of 1982. At this symposium, all of the R&M directors of all the subcompanies within the corporation convened near Los Angeles for a two-day meeting. In the meetings, each company addressed how the R&M function reported within their company. Not unexpectedly, the results covered the spectrum of possibilities--including the Engineering, Quality Assurance, Product Support, Product Safety, Quality Engineering, Product Assurance, Logistics Integration, Systems Effectiveness, Commercial Support, Advanced Systems and Technical Services Organizations, just to name a few.

When the corporate executive was queried as to whether there was any apparent correlation with R&M performance of the various companies and their unique reporting structure, he replied that if so, it was not readily relatable. In follow-up conversations, he related that he had come to understand that the person in the job was the important factor, not how the job reported. In summary, he stated that a "doer" who is interested and supportive of R&M can make things happen in almost any reporting structure within the formal and informal organizational hierarchy.

## (2) Team Concept

A major thread which surfaces looking across successful programs is establishment of a non-adversarial relationship with heavy emphasis on a team approach to problem investigation and resolution. This approach was strongly emphasized on the F-16 radar from the earliest establishment of requirements throughout the entire program. Confrontational negotiations were avoided and the notion of team effort was strongly supported at all levels. This concept was even extended to suppliers where the subcontractor provided assistance to suppliers to ensure

their products were up to the required quality levels. Motivational meetings were held with supplier and employees, awards presented and F-16 films shown. (Ref. F-16 Case Study, p. II B-16.)

For the F/A-18 radar program steps to promote the team concept included collocation of personnel within the same area. For example at the prime contractor's facility the R&M engineers were collocated with the design engineers. (Ref. F/A-18 Case Study, p. 96.)

## 2. Monitoring and Control of Subcontractors

The whole can only be as good as its weakest part. With the trend in the recent decade toward increased levels of subcontracting from the prime contractor level, the R&M role of monitoring and control of subcontractors and suppliers becomes increasingly important. Within each of the successful programs reviewed, particular attention was paid to the performance of subcontractors and suppliers.

Typical of the things done are the following items from the FIREFINDER Program. R&M requirements were allocated to the subcontractor via a procurement specification. The prime contractor conducted design reviews and performed thermal studies and R&M analyses prior to qualification testing. Stress screens were developed. A failure feedback and corrective action system was imposed on the complex/critical items suppliers, and production control testing was monitored to ensure failures attributed to subcontractor items were reviewed by Failure Review Boards. (Ref. FIREFINDER Case Study, p. 84.)

In the case of the F-16 radar program, identification of the TWT as a potentially high risk item and life-cycle cost driver generated the requirement for special management attention. As a result the government and prime contractor jointly devised a reliability test for the TWT and included it in the RFP to

the radar subcontractor. The radar subcontractor in turn imposed a reliability growth test requirement on its subcontractor for the TWT. As a result of this special attention the high-risk item was successfully managed and a field performance over four times higher than the predicted TWT MTBF was achieved. (Ref. F-16 Case Study, pp. II B-18 and II B-19.)

### 3. Engineering Change System

In order to produce reliable and maintainable weapon systems, a formal controlled process must exist to provide for detecting problems, determining solutions, generating changes and then implementing changes into the respective hardware and/or software.

A common thread across the successful programs reviewed both by case study and report research was flexibility in the change process system and/or accelerated approval of engineering changes. Within the F-16 radar program, this was accomplished by processing R&M type changes both as Class I and Class II resulting in excess of 5700 changes. (Ref. F-16 Case Study, p. ID-11.)

In an attempt to quantify ECP proposal flow, data were collected for several programs (see Fig. C-7).

#### ECP PROPOSAL FLOW Change Initiation Through Contractual Approval

<u>Program</u>	<u>Average Flow Calendar Days</u>
E-3A	344
E-4	210
ALCM	164
Roland	178
LDNS	5-30

FIGURE C-7. ECP Approval Cycle

## C. DESIGN

This section describes the processes used on the case study's systems to influence the design and to effect the R&M-related design features.

### 1. Development of Design Requirements

Four of the six case studies that discussed the development of detailed design requirements started with the translation and apportionment of platform R&M requirements to avionics requirements which were then passed to the subcontractors in very detailed specifications. On the F-15, F-16 and F/A-18 radars programs, the prime contractor was allowed to reapportion requirements, or else required design optimization via design alternative studies performed by the subcontractor. The FIREFINDER program's two radars were prime contracts to the Army, who provided the performance and R&M requirements directly to the contractor. LDNS R&M design requirements were developed from user needs and transmitted to the contractor in the development specification. The contractor took a top-down approach where a MTBF number was allocated to each subassembly.

Specific design guides were prepared for the designers in the areas of:

- Parts and material selection
- Derating
- Design practices
- Packaging of electronic equipment
- Partitioning and test pointing for compatibility with automatic test equipment.

The source of these guides ranges from guidance documents provided by the prime contractor, to allowable parts lists, to military specifications, standards and design guides. In all cases, it was indicated that these served as a starting point only, and that

The range for the period from change initiation through contractual approval was 5 to 344 average flow calendar days. Recognizing that activity cannot really commence until change is approved, an inhibitor to improving R&M is built-in. Where there are high production rates, this can lead to costly retrofits and fielding of hardware with known R&M problems. This then contributes to the overall field data and tends to lower the overall reported R&M levels.

In the case of the LDNS, extraordinary procedures were used to minimize the time required for ECP approval. Frequently, Army approval was obtained within 5 days. In all cases, the ECP request was acted upon within 30 days.



considerable concurrent analysis, design alternative studies, design feedback, and design adjustments were made. Strict interpretation of many of these guides allowed exceptions to surface and be effectively managed.

Design alternatives were predominant in choice of components, thermal and environmental considerations and addressed primarily the reliability requirements. Designing of the Built-In-Test (BIT), and the off-line testability requirements benefited from the formal and several automated analytical techniques presented.

Unlike specific direction in parts choice and derating, testability related design features evolve from general design guides, testing of resulting ideas on paper and adjusting and fine tuning the ideas, until there is reasonable confidence that a requirement can be met. At risk is costly redesign.

The process begins with system partitioning into lower-level assemblies and analyzing the ability of fault detecting and isolating to the functional modes created by the partitions, with either test points or BIT facilities. Partitioning was invariably in competition with packaging density, availability of connector pins, size, thermal and performance requirements. The F-15, F/A-18 and FIREFINDER case studies describe how computer techniques were used to provide rapid analyses and feedback to the designer and to guide him into developing the appropriate design.

## 2. Design Alternative Studies

Several deliberate R&M-related trade studies were conducted for the F-15, F-16 and F/A-18 and FIREFINDER radars and the LDNS. The studies examined alternatives with which to best meet, rather than improve upon, the specified reliability, maintainability, BIT and testability requirements. Major issues considered in the studies were risk in meeting specifications, compatibility with performance requirements, ease and practicality of implementation as well as minimizing design impact. Figure C-8 is a

summary of the more significant, deliberate design alternatives that were reported.

<u>SYSTEM</u>	<u>QUANTITY</u>	<u>CASE STUDY PAGE</u>
F-15	5	IIC-7
F-16	7	IIC-9, 11
F-18	6	111
FIREFINDER	9	56/2-8 thru -10

FIGURE C-8. Deliberate R&M Design Alternatives

Whereas the deliberately implemented studies may have provided improvements beyond specified values, significant improvements were realized as a by-product from alternative design studies conducted for performance enhancement, weight reduction, cost reduction, thermal considerations, engineering change proposals or similar reasons. These are summarized in Fig. C-9.

<u>SYSTEM</u>	<u>QUANTITY</u>	<u>CASE STUDY PAGE</u>
F-15	11	IIC-11 thru 21
F-16	5	IIC-13
F-18	3	112 thru 114
FIREFINDER	17	56/2-8 thru 10

FIGURE C-9. Design Alternatives Resulting in R&M Benefits

The summaries indicate that the studies always considered R&M impact and, in turn, life-cycle cost impact, and usually resulted in a substantial improvement. Examination of the design details evaluated in the studies indicates that design improvements, by applying the latest proven state-of-the-art components, packaging and cooling, as well as software techniques, caused improvements in R&M. Figure C-10 graphically depicts the reliability improvements that were realizable from technology growth of electronic components.

The data indicate that trade studies can have a significant impact in establishing the R&M design baseline and an even greater impact on R&M growth as part of a design maturation and improvement program. In planning such growth, an aggressively managed trade study program directed at finding a proper balance between the design issues and the potential gains in R&M is essential to effect R&M benefits from design improvements.

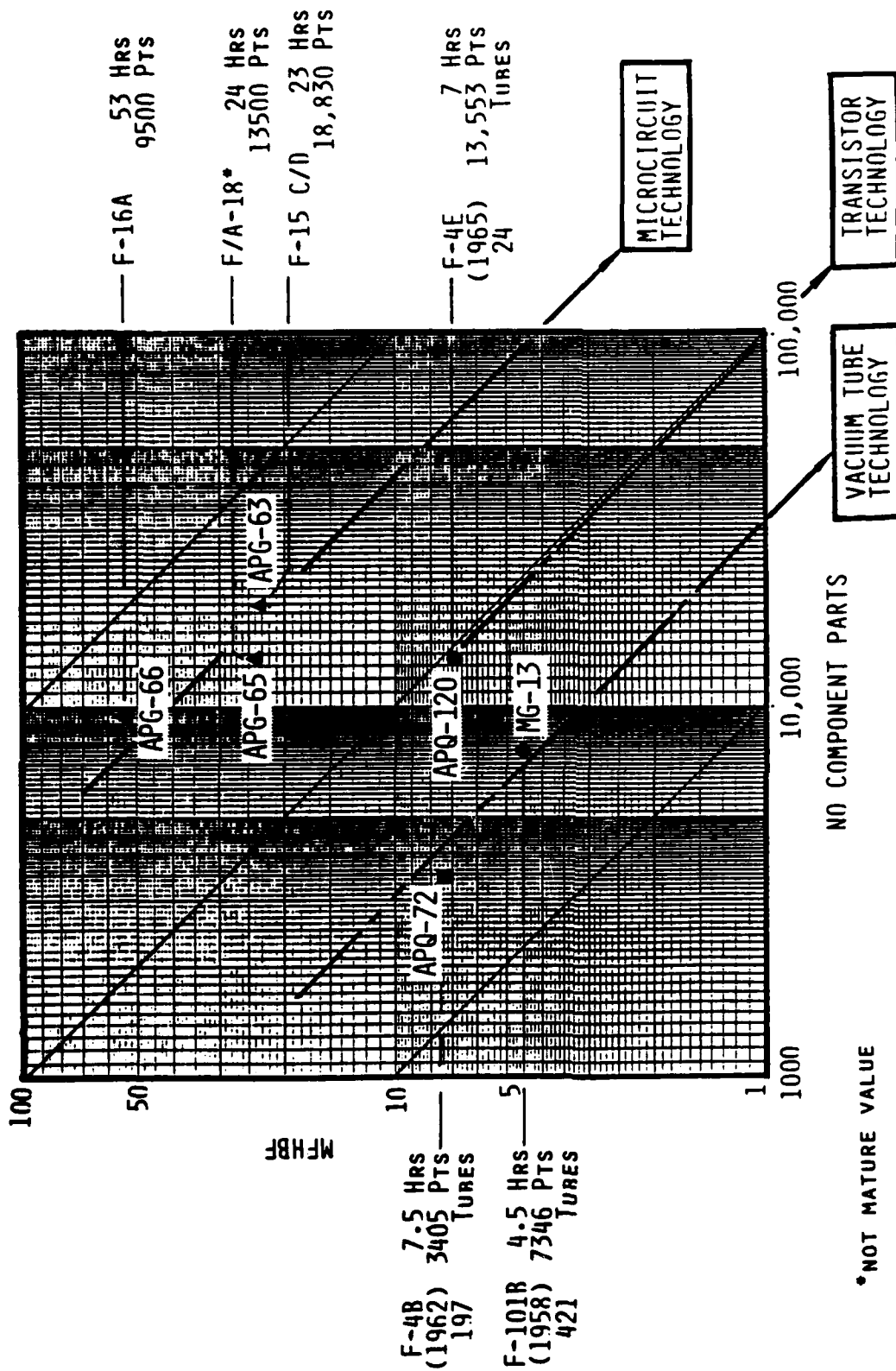


FIGURE C-10. Complexity and Parts Technology Drive Reliability

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### 3. Design Evaluation Analysis

All case studies reported the use of design evaluation analyses as part of the design process and design alternative studies. The results of the analyses were employed in component and material selection, establishing stress levels, and in mechanical and electrical design. Fig. C-11 summarizes the techniques reported.

The case studies do not provide details of the techniques used, from which it may be assumed that military/industry standard techniques were used except for the computerized techniques (asterisks on the figure).

	F-15	F-16	F/A-18	FIREFINDER
Reliability Analysis	✓	✓	✓	✓
Maintainability Analysis	✓	✓	✓	✓
Thermal Analysis	✓	✓	✓	✓
Stress Analysis	✓	✓	✓	✓
FMEA	✓	✓	✓	
Sneak Circuit Analysis			✓	(Antenna & Power Supplies) ✓ (Transmitter)
ORLA	✓	✓		
BIT Effectiveness	✓	✓	✓	✓
Testability	✓	✓	✓	✓

FIGURE C-11. Evaluation Techniques Summary

\*Computerized techniques were employed.

#### 4. Parts and Material Selection and Control

A formal parts and material control process was followed by the F-15, F-16, F/A-18 and FIREFINDER programs with each placing slightly different emphasis on what was controlled, and the degree of the control to effect the specified reliability and standardization requirements. Figure C-12 provides an overview of that control. The prime contractor chaired the parts control board for all three subcontracted radar programs.

	F-15	F-16	F/A-18	FIREFINDER	LDNS
PARTS CONTROL BOARD (PCB) Chaired by Members	Prime Subs SPO	Prime Subs SPO	Prime Subs and Suppliers		Contractor Customer
Support from	DESC RADC	DESC RADC			
PARTS CRITERIA	MIL-M-38510 MIL-STD-883, Class B ER & TX	MIL-M-38510 & MIL-STD-883, Class B ER & TX	MIL-M-38510, ER & TX	MIL-STD-883 MIL-STD-883 Class B & additional 100% high & low temp. testing of selected parts	MIL-P-11268
NON-PREFERRED PARTS APPROVAL	Prime DESC, RADC recommendations	PCB RADC, DESC recommendations		Review by DESC AVG-2:1 standard/nonstandard	Customer
Preferred Parts Specified by	PCB	PCB	PCB NAVAIR approved	Yes	

FIGURE C-12. Parts Control Overview

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The following summarizes the emphasis given to the parts and material programs as stated in the case studies.

- a. F-15 - A parts program for all contractor-furnished equipment was established in the MCAIR reliability program plan and implemented by specific requirements in the procurement specification. Control was exercised by MCAIR review and approval of parts. A preferred parts list was submitted by Hughes. Program instructions were issued which mandated parts selection and controls procedures, parts electrical and thermal derating criteria and a weekly update of computerized module indentured parts lists for review and control of parts selection (Ref. F-15 Case Study, pp. IIC-68,72).

The process led to standardization in module construction with four basic types; standard parts and wiring access covers; standardized module restraint, identification and keying, and a standard cooling system using an integral module heat exchanger.

- b. F-16 - General Dynamics imposed aggressive parts control and standardization requirements on all new designs by specific requirements in the equipment specifications and statements of work. Full government support was provided to develop new military standards for multiple use parts. The military standards available for designers to select from were reduced to those with established reliability requirements.

Commonality was forced by reducing the number of standards available to designers and subcontractors. The F-16 Program Parts Selection List was established after a comprehensive review of military specifications. The number of standards was reduced to only those

with Established Reliability (ER) requirements. The F-16 Parts Control Board maintained constant contact with Rome Air Development Center (RADC) for state-of-the-art device recommendations. Commonality was achieved by selecting standards based on RADC recommendations. The F-16 Parts Control Board reviewed the microcircuit industry and established that the low power Shottky technology would be the leading technology for the 1980s. The 54H and 54L technologies were eliminated from the PPSL. The dual-in-line microcircuit package was selected over the flat pack for the PPSL.

Fastener types were reduced from 226 to 47 and the fastener recess standardized. Limiting the use of high failure rate electromechanical parts resulted in use of only six potentiometers, two relays and four motors.

- c. F/A-18 - An extensive parts control program was established by MCAIR and approved by NAVAIR. The program established parts derating requirements that were more stringent than NASA guidelines which resulted in a high percentage of high reliability and standard parts in the radar (Ref. F/A-18 Case Study, pp. 45B/7-21).
- d. FIREFINDER - Much of the success of FIREFINDER reliability design effort was due to the up-front planning of consistent and standardized requirements which were clearly disseminated to the designer. Allocations were made for reliability which included preferred parts and materials and detailed standards for printed wiring boards. A producibility/standardization guide was also created at the beginning of the radar design phase containing guidelines for parts selection and specified allowable stress levels for all major component classes (Ref. FIREFINDER Case Study, p. 100).



Two approaches to parts control were employed. The first was a strict array parts control plus non-standard parts review and approval by DESC for the AN/TPQ-36 antenna. This resulted in a 2.3 to 1 ratio of MIL standard to non-standard parts with no parts upgrade required. The approach used for the AN/TPQ-37 antenna employed industrial standard and GSG standard parts without requiring non-standard parts approval. This resulted in a 1.84 to 1 ratio of MIL standard to non-standard part types, but required 46 semi-conductor upgradings to meet temperature range requirements; 47 components required upgrading by burn-in prior to acceptance tests and alternate source development for 63 parts. The AN/TPQ-36/37 common shelter was influenced by both AN/TPQ-36/37 and as a result, achieved a ratio of 1.98 to 1 (Ref. FIREFINDER Case Study, pp. 94, 95).

- e. LIGHTWEIGHT DOPPLER NAVIGATION SYSTEM - The MIL-P-11268 specification was a contract requirement. The parts control and selection was managed through a government/contractor parts control board. The use of standard parts was stressed. Deviation from part selection and material selection control was granted by government (project engineer or project manager). The contractor was required to show cost advantage or reliability improvement. Project personnel control of the board expedited the selection process. Configuration control was not enforced until the completion of testing to alleviate cumbersome procedures (Ref. LDNS Case Study, p. 65/1-17).

## 5. Derating Criteria

The component derating criteria for the four case studies were established by a reliability policy/plan as required by the individual contracts. Stress levels were based on standard levels developed either by the prime contractor or manufacturer with no details provided for tailoring to a specific application, as follows:

a. F-15 - stress levels were contractually imposed by MCAIR's reliability program. Changes required MCAIR approval (Ref. F-15 Case Study, p. II C-78).

b. F-16 - stress levels set by the subcontractor with General Dynamic's approval. Levels were tailored to the environment and intended use and verified by stress analysis.

c. F/A-18 - standard NASA stress levels were tailored to the application based on trade-offs made during the proposal phase for the radar. The levels were included in the procurement specification. Verified by stress analysis.

d. FIREFINDER - the derating requirements were set by the Army with detailed levels established by the manufacturer's producibility/standardization requirements as part of his reliability program. These were provided to the designer in the form of derating and application guidelines. Less than 0.1 percent of overstress was reported from testing and operational use and these were cleared with relatively little impact on the program (Ref. FIREFINDER Case Study, p. 106).

a. Derating Parameters

The electrical parts derating levels for circuit components are listed in Fig. C-13 for the AN/APG-63, AN/APG-66 and AN/APG-65 radars. Details for the FIREFINDER antenna/transceiver and common shelter were not available. In addition, the AN/APG-63 lists the following:

- Relays: 10% with a lamp load  
20% with an inductive load  
40% with a resistive load
- Switches 50% of rated current
- Motors 50% of rated load
- Gears 60% of rated load
- Bearings 60% of rated load

(Ref. F-15 Case Study pp. II C-83, 89, 90).

	AN/APG-63 (F-15)				AN/APG-66 (F-16)				AN/APG-65 (F/A-18)			
	POWER DERATING	VOLTAGE DER.	CURRENT DER.	MAX J <sub>t</sub>	POWER DER.	VOLT DER.	CURR DER.	MAX(2) J <sub>t</sub>	POWER DER.	VOLT DER.	CURR DER.	MAX J <sub>t</sub>
<u>MICROCIRCUITS</u>												
TTL												110°C
CMOS								60%				90°C
OTHER			70%	100°C				60%				100°C
<u>HYBRIDS</u>												105°C
<u>TRANSISTORS</u>												
GENERAL PURPOSE	30%	70%	70%	100°C		60%		60%	.30	.60	.50	100°C
POWER	30%	70%	70%	105°C		60%		60%	.30	.60	.50	105°C
<u>RESISTORS</u>												
FILM	50%				50%(1)							
COMPOSITION	50%				50%							
WIRE WOUND (ACC)	30%				20%							
" " (PWR)	40%											
<u>DIODES</u>												
GENERAL		70%	20-70%	100°C		60%		60%	.30	.50	.50	100°C
POWER		60%	50-80%	105°C		60%						
ZENER		20-40%		105°C		60%						
<u>COILS, CHOKES &amp; TRANSFORMERS</u>		60%	70%			60%	60-70%					
<u>CAPACITORS</u>												
CERAMIC		50%				60%(3)			50%			
TANTALUM, SOLID		50%				60%						
GLASS		60%										
MICA		50%										
PLASTIC		40%				60%						

(Ref. F-15 Case Study, pp. IIC-78 to 91; F/A-18 Case Study, p 126.)

(1) Derating = P dissipated/p allowed; (2) 60% T<sub>J</sub> dissipated/p allowed; (3) Also temperature derated due to AC ripple.

FIGURE C-13. Parts Derating

b. Exceptions to Derating Criteria

Only the AN/APG-65 (F/A-18) case study reported derating exceptions, listing those applications with stresses in excess of 103 percent of the derate value. Figure C-14 lists the parts involved together with the reason alternate parts could be used. Seventy-five of the 94 parts required exceptions due to overstressing and 19 due to overtemperature. Many of the overtemperature problems were solved by thermal packaging redesign.

The 94 parts represent less than 0.7 percent of the total parts count of 13,500.

	WT. & VOLUME	VOLUME	LACK OF PART TYPE	STAND.	OTHER	TOTAL
Capacitors	9	13	4	-	10	36
Resistors	--	-	2	-	2	4
Diodes	--	8	9	-	22	39
Transistors	--	--	7	2	-	9
Inductors	5	--	--	-	-	5
ICs	-	--	1	-	-	1
TOTAL	14	21	23	2	34	94
	15%	23%	24%	2%	36%	

(Ref. F/A-18 Case Study pp. 131-136).

FIGURE C-14. AN/APG-65 Derating Exceptions

## 6. Thermal and Packaging Criteria

The thermal and packaging criteria were based on the allowable parts temperature, environmental requirements, cooling air availability and restrictions on construction. This is illustrated graphically in Figure C-15, the thermal design consideration for a module taken from the F-15 case study. Restrictions to the design freedom for thermal considerations included size, weight and shape restrictions; vibration considerations material priorities for structural considerations; parts types and their mounting requirements; and manufacturing techniques.

Trade-offs were made to address all of these requirements, from which the final designs evolved. The major areas of thermal design considerations presented in the case studies were:

### a. F-15

- Integral module heat exchanger selected for dramatic thermal performance improvement.
- Flatpacks and surface mounted discretes selected for their lower thermal impedance, easier removal and higher packaging density.
- Bonded crushed honeycomb design selected for both light weight and a reduced transmissibility of 3 to 5 vs. approximately 20 for conventional designs.
- Cooling air is introduced at unit rear panel and exhausted through bottom cover.
- Central (or side) unit air plenum distributes air to all modules in parallel.
- Air is metered by orifices in module inlet manifold.

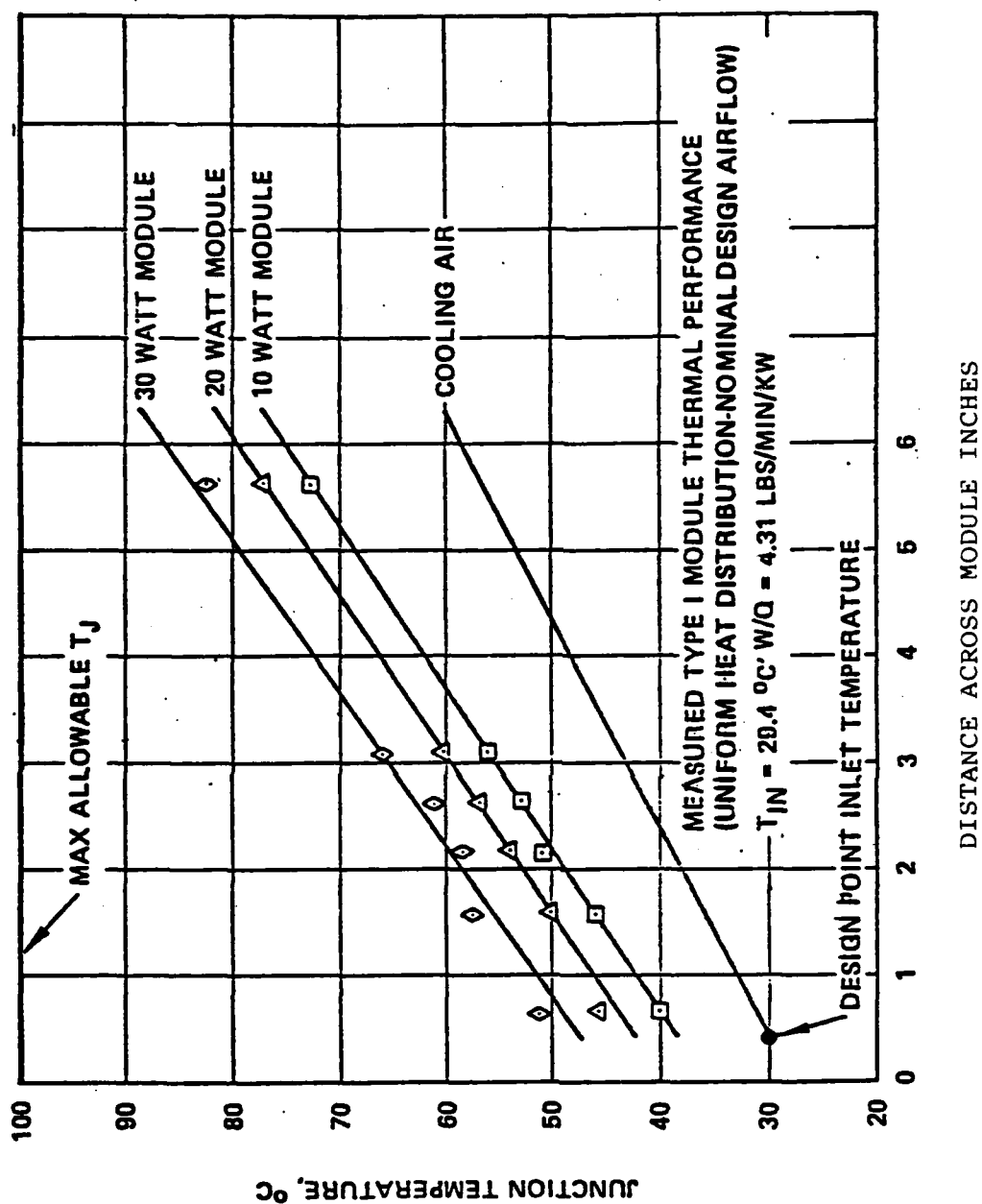


FIGURE C-15. APG-63 Module Thermal Design  
(Ref. F-15 Case Study, p. IIC-44)

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- Inlet and exhaust manifolds provide uniform air flow through manifold by establishing equal length flow path (Ref. F-15 Case Study, pp. 48-52).

b. F-16

- High power components were placed nearest the edge or coolest part of the subassembly.
- Copper heat sinks were used rather than aluminum in several critical locations.
- Circuit boards were arranged for efficient cooling.
- Cooling air was apportioned between LRUs.

c. F/A-18

Refinement of the F-15 heat exchanger consisting of a lightweight aluminum heat exchanger sandwiched between two multilayer printed wiring boards affords 15° to 20°C temperature reduction of components (Ref. F/A-18 Case Study, p. 120).

d. FIREFINDER

Blowers and air ducts through cold plates were used to cope with desert environment. The higher power AN/TPQ-37 transmitter required liquid cooling (Ref. FIREFINDER Case Study, p. 110).



## 7. Computer-Aided Design

Computer-aided design (CAD) is an analytical tool which can automatically evaluate and optimize a design attribute. Until recently, it has been used primarily for system/equipment structural and performance-related design requirements. Though the case studies do not address the topic directly, evidence of the application of some level of CAD for R&M is found in the description of analytical processes for the F-15, F-16, F/A-18 and LDNS, as follows:

- a. The F-15 program reports the use of computerized thermal analysis and design, BIT analyses and automatic test generation.
- b. The F-16 program reports a computerized optimum repair level analysis as a trade-off tool and a computerized analyses thermal and computerized production in the radar's design.
- c. The F/A-18 program describes the use of a computerized sneak circuit analysis and thermal analysis for circuit design.
- d. The LDNS reports the use of computerized worst-case analysis.

The FIREFINDER and AEGIS programs do not describe CAD techniques.

Computer-aided design for R&M has rapidly expanded to include interactive R&M predictions, the evaluation of electrical, thermal and mechanical stresses, sneak paths, test point planning, BIT strategy and software design, choke points, testability and other issues that can aid or provide automatic decisionmaking for forward-going design or the evaluation of design alternatives. Computer-Aided Design (CAD) examples from the case studies dealt with specific areas. CAD had not yet evolved to the point that enabled linking many of these areas into an automated interactive design process.

The details presented in the case study of the few applications of R&M-related CAD that were discussed indicate a high potential payoff in the application of contemporary and new CAD technology in the design process, particularly in the area of BIT, testability and diagnostics preparation.

8. Testability Analysis. All six case studies describe the process of developing the design in the area of testability, with varying degree of detail. The analytical processes described are included in an overall iterative design requirements/evaluation/analyses process forming a part of formal design control addressing R&M.

All case studies used formal program plans and formal prime contractor/government controls which specified the process, and all indicate that the specified requirements were translated to the designer. Though no timetable is given, it can be assumed from the availability of analytical results at design reviews that design direction took place at the very beginning of the programs.

The results of the process shown in Fig. C-16 are indications that the very stringent specified requirements were demonstrated to have been met, or slightly bettered. The F/A-18 case study provided a brief discussion of the potential of the BIT to fault isolate to subassemblies (SRAs), though not required, does exist.

SYSTEM	TECHNIQUE USED	RESULTS
F-15, AN/APG-63	BIT: computerized design analysis for design feedback/changes <ul style="list-style-type: none"> <li>• Formal design reviews</li> <li>• FMEA</li> <li>• Mathematical evaluation for random faults</li> </ul>	Video tape recordings for organizational level fault isolation
	Field/Depot Testing: <ul style="list-style-type: none"> <li>• Computerized digital simulation and test and sequential automatic test generator</li> </ul> (Ref. F-15 Case Study, pp. 102-110).	Fault detection 89.7% to 99.9% isolation to single component with guided probe
F-16, AN/APG-66	BIT: effectiveness analysis <ul style="list-style-type: none"> <li>• Formal design reviews</li> <li>• Checklists</li> </ul>	Fault detection 94% Fault isolation 98%
	Field/Depot Testing: <ul style="list-style-type: none"> <li>• Test tolerance analysis</li> <li>• Checklists</li> </ul>	Fault isolation 96%
F/A-18, AN/APG-65	BIT: effectiveness analysis <ul style="list-style-type: none"> <li>• FMEA</li> <li>• Sneak circuit analysis</li> <li>• Formal reviews</li> <li>• Special BIT monitoring team</li> <li>• Field/Depot Testing</li> <li>• Design guides</li> <li>• Sneak circuit analysis</li> </ul>	Fault detection 90.4% Fault isolation 85.4%  Potential for isolation to sub-assemblies

FIGURE C-16. Testability Analysis Summary

SYSTEM	TECHNIQUE USED	RESULTS
FIREFINDER AN/TPQ-36 AN/TPQ-37	BIT: computer simulation of the signal processor group	Fault detection 90% Fault isolation 90%
	• Test point placement by design engineers	Computerized fault isolation assist
	Field/Depot Testing: • Test program generation	EQUATE compatible
AEGIS	Design reviews (no details)	(no details)

FIGURE C-16. cont'd

#### 9. Testability Verification and Testing

The verification and testing of the testability attributes in the course of the design process (as distinguished from formal demonstration and field tests), was accomplished with the analytical tools described in subparagraph 8 above.

The F-16 case study reports a pre-demonstration design evaluation in addition to the analyses by inserting 1462 faults to test fault detection capabilities. This is ten to twenty times the normally demonstrated quantity.

The F/A-18 case study describes a formal analytical verification program imposed by the prime contractor and the FIREFINDER reports a deliberate manual testing of every test point to verify that injected faults could be detected by BIT.

#### D. MANUFACTURING

In the area labeled as production, the case studies examined two specific areas of activity: environmental stress screening and the failure reporting, analysis and corrective action system. Both of these activities span the development as well as the production phase, but their primary focus and impact is on the reliability and maintainability of manufactured items, as opposed to the R&M of the design of the equipment. In examining these areas, the case studies did review the two subjects during the development phase.

##### 1. Environmental Stress Screening of Parts and Equipment

Environmental stress screening (ESS) has been defined as: "The process or method whereby a group of like items are subjected to physical stress to identify and eliminate latent part and manufacturing defects prior to field deployment" (Ref: RADC TR-82-87). ESS is unlike the tests that are normally associated with reliability development since it is designed to stimulate the precipitation of defects, not to simulate the operational environment. The specific screening methods are tailored to the specific part or workmanship defects that are expected or predicted.

##### a. Levels of ESS

ESS is applied at various levels of assembly; piece part, module, unit, and system level, for the F-15, F-16, F/A-18 and FIREFINDER radars. Each radar contains "hi-rel" parts, including MIL-M38510 microcircuits which are extensively screened to MIL-STD883 by the part manufacturer. In addition, each radar manufacturer conducts on-receipt testing of selected components. This includes part screening comprised of 100 percent test-at-temperature (including functional) for microcircuits, PIND (Particle Impact Noise Detection) testing for large cavity devices, (transistors and diodes), and special tests on selected devices. Screening at the module (SRA/SRU), units (WRA/LRU) and set (system) are conducted differently among the four radars. Figures C-17 through C-19 summarize ESS.

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	F-15 RADAR	F-16 RADAR	F/A-18 RADAR	FIREFINDER RADAR
PARTS	IC's & HYBRIDS	IC's & HYBRIDS	IC's & HYBRIDS	IC's & HYBRIDS
MODULE	YES	YES	YES	CONSIDERING
UNIT (OR BOX)	YES (4 OF 9 LRUs)	YES (1 FAILURE- FREE CYCLE)	YES (3 FAILURE- FREE CYCLES)	SELECTED UNITS
SYSTEM	YES 24 OP HRS (3 FAILURE- FREE CYCLES)	NO	YES 25 OP HRS (5 FAILURE- FREE CYCLES)	YES 100 HRS (25 FAILURE- FREE CYCLES)

FIGURE C-17. Stress Screening Use

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APG-63 (F-15)  
 APG-65 (F/A-18)

F-16

SRA/SRU LEVEL

- Temp	-60°C to +95°C	-40°C to +71°C
Rate of change	15°C/MIN	15°C/MIN
Cycles	46	1
Duration	23 HRS	Various
On-time	NONE	NONE
Test-at-temp	Functional Test @ Room Temperature	Verify at -40°&+71°Extremes
Failure free	N/A	N/A
- Vibration	NONE	RANDOM (REC/REF SOURCE)
Duration	N/A	2 min/20 min operate
Failure free	N/A	3g RMS
		N/A

FIGURE C-18. SRA/SRU (Module) Screening

<u>WRA/LRU LEVEL</u>	<u>APG-63 (F-15)</u>	<u>APG-66 (F-16)</u>	<u>APG-65 (F/A-18)</u>
- Temp			
Rate of change	-54°C to +50°C	-54°C to +71°C	-55°C to +55°C
Cycles	20°C/MIN	15°C/Min	15°C
Duration	32	4 1/2 Hrs/Cycle	12
On-time	40 HRS	2 1/2 Hrs/Cycle	24 HRS
Test-at-temp	24 HRS	-40°C & +71°C	13 HRS
Failure free	-54°C & +50°C	1	-40°C to +55°C
	1 CYC		3
- Vibration	NONE	RANDOM (COMBINED)	6g RMS RANDOM
Duration	-	2 min/20 min Operate	20 MIN
Failure free	-	1	YES
<u>SYSTEM LEVEL</u>			
BURN-IN			
- Temp			
Rate of change	-65°C to +70°C (Chamber)		-54°C to +71°C (Chamber)
Cycles	5°C/MIN		5°C/MIN +46°C (Coolant)
Duration	15		5
On-time	24		35 HRS
Test-at-temp	-40°C & +71°C		25 HRS
Failure free	3 CYC		-40°C to +46°C
			5
- Vibration			
Duration	2g Sine		2g Sine
	30 MIN/CYC		10 MIN/HR
			Combined with Temp

Figure C-19. WRA/LRU (Unit) Screening



The significant differences are:

- At the module (SRA/SRU) level, the F-16 modules were subjected to temperature cycles from -40°C to +71°C with two minutes of random vibration for every twenty minutes of operation and then it was verified that the module works at low (-40°C) and high (+71°C) temperatures. The F-15 and F/A-18 radar modules were subjected to temperature cycles at greater extremes (-60° to +95°C) without vibration and function tests were conducted at room temperature only.
- The F-16 and F/A-18 employ random vibration at the unit (WRA/LRU) level whereas the F-15 does not. (Implementation not available when F-15 production began, next generation F-15 radars will include random vibration.)
- At the system level, the F-16 set does not receive burn-in per MIL-STD-781B (temperature cycling with sine vibration.) Starting in January 1983, a self-imposed five-day sample test on one radar per month using the RQT thermal cycling was initiated. Each F-15 and F/A-18 set receive 48 hours and 35 hours of burn-in, respectively, before delivery.

The ESS program for the APG-65 F/A-18 radar was built on experience gained on the APG-63 F-15 program. The conditions used in the APG-65 ESS have evolved considerably from those initially imposed at the beginning of the program. Evolution has been toward shorter minimum screens but longer "failure free" intervals. The use of "failure free" cycle requirements allows shorter screening on units with no screening failures and imposes additional screening time on units that are experiencing failures. F-15 and F/A-18 experience indicates that flexibility is needed in establishing screening methods and specifications and that supplier involvement is necessary.

The FIREFINDER screening program included high-temperature tests of ICs at receiving inspection initially with the program being in the process of changing the requirement to tests at both high and low temperature. Selected complex equipments were screened at the supplier or in-house and the system was subjected to high-temperature burn-in at 50°C for 100 hours with the last 24 required to be "failure free" (Ref. FIREFINDER, pp. 56/2-22). Additional screening using temperature cycling and low temperature test at the signal processor unit level is being developed.

## 2. Progress in the ESS Area

With the increasing complexity of modern electronic systems, there has been increasing attention to the area of environmental stress screening. There have been a number of recent studies attempting to gather the best information on this subject and to provide direction and guidance to the engineer or manager who is attempting to structure an effective environmental stress screening program. In the course of the study, a variety of these activities was reviewed. The most comprehensive of these efforts is the National Program on Environmental Stress Screening of Electronic Hardware (ESSEH) by the Institute of Environmental Sciences. The program was initiated in 1979 to attempt to bring some order and consistency to ESS. The situation at that time was typified by most of the industry working unilaterally with the results of these efforts being unpublished and unshared. The ESSEH program has attempted to gather this experience together and to make a usable guideline for others to use. The initial IES guideline on ESS was published in 1981. A continuing effort is directed at updating this guideline and adding information on part screening and updating assembly level screening guidelines.

Among the other recent studies on this subject that were examined by the study was the RADC technical report (RADC TR-82-87), Stress Screening of Electronic Hardware. This report and the work currently being accomplished on RADC contract F-30602-82C-0121 will serve as the basis for a draft standard on ESS. ESS cost considerations are discussed in Appendix F.

### 3. Failure Reporting Analysis and Corrective Action System (FRACAS)

A system for identification and correction of failure modes/problems is essential to design maturation and reliability growth. The cases make a strong statement that a closed loop failure reporting, analysis and corrective action system, emphasized by program management, established early in the development effort and continued through production, is effective and provides cost benefit. The earlier in the system life the problem is identified and corrective action applied, the less costly in dollars and perturbation to the system it is.

The FIREFINDER case study makes the point that upper management participation and assignment of a responsible person are keys to a successful/effective FRACAS. For FIREFINDER, the Failure Review Board (FRB) was the focal point for reviewing the status of all failed items reported on Operation and Maintenance Reports (OMRs), field failure reports and other reported problems through the Responsible Assigned Engineer (RAE).

FIREFINDER OMRs were written by systems test personnel for all operational and/or maintenance discrepancies occurring. Failed hardware is dispositioned by the RAE. Preliminary Review Team (PRT) reviews all OMRs, field failure reports or other failure data, and assigns them to the appropriate RAE for resolution. Factory failure trend data are compiled by Quality and the Project Offices for FRB review. The FRB assigns problems to the RAE. The FRB monitored progress of the RAE activity in regularly scheduled weekly meetings, reviewed corrective actions per flow diagrams and closed items as warranted. Test discipline assures that information required for good analysis is preserved. Test discipline is addressed in test procedures in strict implementation of those procedures, and in independent review of failure reports to assure completeness (Ref. FIREFINDER Case Study, p. 140). A key aspect of the FIREFINDER FRB is the involvement and responsibility of the engineering activity. The technical director is the Chairman

and he is directly responsible to management for FRACAS effectiveness. He is assisted by co-chairman from reliability and product assurance (quality).

The F-15 and F/A-18 radar cases made reference to the CLEAR system as a valuable/effective FRACAS. The cases stated that early in the 1970s, MCAIR developed the CLEAR (Closed Loop Evaluation and Reporting System) to satisfy F-15 program needs for reliability, maintainability, and quality engineering information in addition to being complementary with the AFM 66-1 system. CLEAR integrated into one system what had previously been many separate MCAIR information gathering systems to provide nonconformance, malfunction, maintenance, and safety data. In addition to combining data sources, new multipurpose forms were designed and used to input information more efficiently into computer systems, thereby minimizing manual operations and providing expanded analysis and reporting capabilities. CLEAR is used during production, assembly, laboratory testing, supplier testing, flight testing and initial field operations, or where MCAIR is providing repair and support services. The system provides computerized outputs which are used to fulfill F-15 contract requirements for reliability, maintainability, and quality reporting. The case stated that the three major building blocks of CLEAR (reporting, input, and computer processing) have been improved steadily with time and adapted for use on the F/A-18 and currently the AV-8B (Ref. F/A-18 Case Study, pp. 166-168).

An F-16 Radar Field Performance Evaluation group was initiated in 1980 to provide R&M field performance visibility to management and engineering and to identify R&M problem areas. An R&M computerized data base has been generated with input data from contractor field engineers and the RIW data base. Problem areas identified by an analyzer of this data are provided to the "Problem Action Team" for evaluation, resolution and reporting to program management. Periodic R&M performance visibility reports are also derived from the data base for distribution to management and design engineering.

## E. TEST AND EVALUATION

The F-16 radar case study states that the program used a great many different kinds of tests to identify and correct problem areas and verify compliance with specified requirements.

The tests and evaluations were grouped into four categories: laboratory tests (development and production), DT&E flight test (development), OT&E flight test (operational), and in-service assessment. Development laboratory tests included Thermal Analysis Verification, Reliability Growth, Reliability Qualification, Maintainability Demonstration and AIS compatibility tests. Production tests included Reliability Growth, Reliability Qualification and Reliability Acceptance tests.

The F/A-18 grouped test and evaluation into: development test, reliability development test, design limit qualification test, reliability demonstration, initial BIT assessment, maintainability demonstration, flight assessment, and in-service R&M assessment (Ref. F/A-18 Case Study, p. 184).

The case study analysis examines six general areas. The six areas are: integrated testing, design limit (environmental) qualification tests, R&M growth/maturity testing, demonstration testing, operational testing, and in-service testing.

### 1. Integrated Testing

The cases studied indicated that most tests can provide data that can be used as indicators of inherent reliability and for discovery of pattern failures/system reliability flaws. The F/A-18 test and evaluation program was purposely integrated and interleaved with many of the individual tests building on one another. All (test) failures were analyzed and followed up for necessary corrective action (Ref. F/A-18 Case Study, p. 185).

Most of the F-15 radar LRUs had elapsed time indicators, and early radar experience came from periodic readings made throughout the development program. These readings and the test data from various tests could be used to predict subsequent reliability

(Ref. F-15 Case Study, p. IIE-2). Results of many tests can be indicators of expected reliability during operation usage. The cases point up the fact that all development tests are sources of R&M data for failure analysis, R&M indicators and corrective action. The developing and changing configuration and the test environments may not replicate the final configuration environment and may not allow a direct measure of final system R&M characteristics, but the value of the data in accessing/improving R&M should not be dismissed. Modifications to the various development tests may be necessary to enhance the value of the data for use in R&M evaluations and improvement, or vice versa, but the value can be seen as indicated in the F/A-18 study. The F/A-18 study makes a point throughout the case that all test results support a TAAF effort, not just a dedicated growth/TAAF test phase (Ref. F/A-18 Case Study, p. 185).

## 2. Design Limit Qualification Tests (Environmental Qualification Tests)

The AN/TPQ-36 Environmental Testing included Qualification Testing of the system in extreme environments during engineering development. Corrective actions instituted to correct Qualification Test problems and enhancement developed using Qualification Test Results contributed to the improvement in R&M characteristics during the engineering development phase. Verification of corrections and qualification of the TPQ-36 design was provided by the First Article Test Program. Performance in extreme environments was also tested periodically throughout production as a part of program testing (Ref. FIREFINDER Case Study, p. 144).

The F/A-18 study makes a point that to minimize the probability of retrofit, high stress testing must be performed early in the program, and the results of all testing must be used in a TAAF (Reliability Growth) concept (Ref. F/A-18 Case Study, p. 188).

The F/A-18 utilized stress tests that subjected the equipment to low and high thermal extremes, with a rapid rate of change between the extremes, to reveal any weakness related to the high rates of change in temperature (Ref. F/A-18 Case Study, pp. 190-198).

The F-16 utilized testing during development and during production under combined environments. These included random vibration, rapid temperature excursions, power cycling and limited altitude and humidity stresses. The testing was conducted to provide early detection and correction of problem areas and to enhance compliance with specified R&M requirements. Extensive use was made of random vibration and temperature profiles that were representative of actual flight conditions during demonstrations.

The Design Limit Qualification test on the LDNS tests was performed in accordance with the test procedures of MIL-STD-810, 461, and 704. The purpose of the tests was to determine how the equipment would operate under the environmental conditions imposed. Failure analyses were performed on failed components and verification of repairs accomplished. No data were collected to calculate R&M limits. The sequence of tests was arranged such that all nondamaging tests were performed prior to damaging tests. It is interesting to note that all qualifications tests were completed prior to Reliability Demonstration Test.

### 3. R&M Growth/Maturity Testing

Each case discusses a R&M growth phase. The F-16 and TPQ-36 had dedicated/planned R&M growth test phases, while the F-15 had specified hardware and software corrective action phases that translated to growth effort, and the F/A-18 made a strong point that all testing was in fact TAAF testing since all malfunctions would be analyzed and fixes fed back into the system. A formal reliability growth testing was not part of the LDNS Engineering Test Program; however, reliability growth was accomplished as part of

the RIW phase. The philosophy of growth testing was evident in each case and R&M growth was tracked as a valuable management tool in each case. Growth charts, plans, projections, programs and analyses are evident, to various degrees, in each case studied.

a. Reliability Growth Tests

The TPQ-36 reliability growth tests were conducted late in the program (during the production phase). The objectives of the growth tests were to use the TAAF principle to surface and correct deficiencies in design parts or workmanship. The two "growth radars" were operated in a simulated field environment including system on-off cycling, Munson road travel and march order emplacement. The two systems accumulated 2800 operating hours (in 6 months on each) and 200 non-operating hours over the Munson road course. All potential fixes were proofed and verified for inclusion into production units (Ref. FIREFINDER Case Study, pp. 152, 153).

On the F-16 radar program, 1500 test, analyze and fix hours were expected to mature the FSD model to achieve the 60 hour MTBF required in the APG-66 Reliability Qualification Test (RQT). Following the 1500 hours growth test, and RQT, an additional 500 hour dedicated growth test (RGT) was planned. The 2000 hours of growth testing were expected to mature the production model radar to the 100 hour MTBF level. Four test articles were planned for the RGT. In actuality one test article was used for the RGT for a total of 420 hours with 23 corrective actions taken.

During the F-16 competition for a radar supplier, it became evident that the TWT was a high-risk item and likely to be a cost driver. A reliability test requirement for the TWT was devised and included in the RFP. The selected radar contractor then further imposed a reliability growth test program on their TWT contractors. The field results of this TWT growth program were



judged so outstanding that the next generation of TWT also has a similar reliability growth program specified. The successful design currently has demonstrated four times the MTBF predicted originally.

The F/A-18 radar program treated all tests as test, analyze and fix (TAAF.) However, a reliability development test (RDT) was conducted using two preproduction radars for a total of 1592 equipment hours. The RDT was conducted in operationally representative environments. Approximately 136 failures were encountered during the RDT. The RDT was judged to have made a significant contribution to reliability growth although its timing was such that many of the problems identified had been found during other tests (Ref. F/A-18 Case Study, pp. 190-197).

b. Total Program for Reliability Growth

The case studies indicate that reliability growth planning was important to the reliability levels achieved by the systems studied. Growth was not just the result of dedicated TAAF phases, but must include failure analyses, corrective action determination for every test, the incorporation and verification of corrective actions, and application to developed systems. The case studies indicate that a growth program is valuable from design through field use. The strong emphasis in the F/A-18 case study on the value of all test data as potential growth test data should not go unnoted. The fact that each program addressed a reliability growth program, and indicated management attention directed to planned and achieved reliability goals/thresholds, is positive indication of the value successful program managers place on a total growth program.

The case studies reveal that treating every failure/incident as a potential opportunity to reduce the failure rate pays big dividends. The F/A-18 radar case study indicates that the ongoing production screening/burn-in and corrective action efforts resulted

in continued reliability growth during the early phases of fielding. The early F/A-18 radar improvements were expedited by contractor field teams that moved from base to base to incorporate planned corrective action modification.

The F-16 radar case study indicates that production reliability growth testing, reliability qualification, and reliability acceptance testing as well as burn-in/screening tests were strong contributors to continued reliability growth in production. Failures were analyzed and corrective action was implemented for problem areas identified during each test including failures during successfully completed reliability qualification and reliability acceptance tests.

The TPQ-37 experienced an abrupt increase in reliability emphasis when the lack of an advanced development reliability requirement was replaced by a firm 90-hr MTBF requirement for low-rate initial production (LRIP) (Note: there was no ED phase). Every part of the LRIP effort became a potential input to a program of reliability growth. The success of this effort is illustrated by the increase in the DT I/OT I MTBF from 24/45 hr, respectively, to 87/94 hours MTBF in DT III/OT III.

A more complete discussion of the value of Reliability Growth program and a summary of how to structure the program are presented in Section IV-B of this volume.

#### c. BIT Maturation Program

The case studies reinforce the concept that for the BIT design to mature, BIT failures must be experienced or, at least, the BIT must see equipment failures. As an example, the F-15 case displays extensive "software corrective actions" resulting from each of the R&M tests. It is noted that a large portion of the corrective actions involve BIT enhancements and a large portion of those involve software changes to reduce false alarms. A goal of BIT maturation is to reduce false alarms, and thus increase confidence in BIT (Ref. F-15 Case Study, p. IIE-27, 28).

A large amount of testing provides the opportunity for obtaining data on hard failures to exercise the BIT. Hence, hard failures decrease. It is important to obtain data in all testing to help mature BIT. As the hardware reliability improves, it is necessary to insert faults to evaluate growth BIT. Data should be obtained and evaluated on all tests to minimize false alarm problems. See Section IV-C for an extensive discussion on BIT diagnostic growth.

The F/A-18 initial BIT assessment conducted in May, 1980 was an early hardware and software evaluation of the supplier's BIT design. These tests were conducted prior to the reliability development test. The BIT isolated approximately 77 percent of the faults inserted. This early test helped to focus the maturation effort.

The formal F/A-18 BIT test, to be conducted later in 1983, will use randomly selected faults proportionally distributed in accordance with WRA failure rates, to test the maturity of the BIT. The test accept criteria is quite stringent (0 test failure allowed for 95 faults, one test failure will require 30 additional faults to be inserted with test failure, and so on) (Ref. F/A-18 Case Study, pp. 202, 203, 207).

The TPQ-36/37 emphasized early maturation of BIT by design and test of BIT along with card design. The contractor attempted to test every failure mode and failure location. The plan was very effective and showed maturity very early in the program. BIT maturity and confidence rose early enough in the program that BIT was used as the indicator in the reliability demonstration tests.

F-16 radar BIT improvements were made at ECP 331, block change point. Several changes were made to the self-test and BIT. The improvements were made to enhance pilot and maintainer confidence and ease of use (Ref. F-16 Case Study, p. IIE-62).

A more complete discussion of maintainability growth program is presented in Appendix E.

#### 4. Demonstration Testing

Demonstration testing, properly specified and implemented, can be a powerful tool for assuring reliability growth to specified levels and providing leverage and engineering data for incorporation and evaluation of corrective action. Each case study contains charts of test results that may be consulted for detail. Figure C-20 is a summary of the type and depth of the demonstrations.

In the case of the APG-66 radar, Reliability Qualification Tests (RQT) and Reliability Acceptance Tests (RAT) were judged by the contractors involved to be among the major reasons the radar has done so well in terms of field reliability. The APG-66 reliability test program included development growth testing followed by development RQT and production growth testing followed by production RQT and RAT. Each test resulted in incorporation of extensive corrective action. In addition, demonstration tests resulted in retest to evaluate effectiveness of corrective action and demonstrate compliance with required levels of reliability. Corrective action was identified and incorporated for all failures including those that occurred in demonstration tests that satisfied the accept/reject criteria. Production RQT and RAT are effective in identifying production problems not relatable to development and verifying their fixes.

The F-16 radar program attempted to hold to schedule (the only slip was a 6-8 month FSD RQT slip due to hardware unavailability). A FSD pre-RQT was performed which was expected to improve the probability of passing RQT. The system, at the completion of FSD growth testing, was submitted to the FSD Reliability Qualification Test. The system failed in the first attempt, corrective actions were implemented and it passed in the second attempt. The production RQT required three attempts before the system successfully passed the test. The production system was submitted to a production acceptance test and was rejected on the first two attempts, and was passed on the third attempt.

	RELIABILITY DEMONSTRATION(1)	TEST CONDITIONS	M DEMONSTRATION (3)	B I T D I
F-15 (APG-63)	RQT PRT PRT	781B TEST LEVEL F(6)	MTTR .77/.365 (2) MTBMA 15/22 (2)	None
F-15 GTWT (APG-63)		781B LEVEL F	N/A	N/A
F-16 (APG-66)	FSD RQT PROD RQT PROD RAT	781B (4) LEVEL F	Mean Task Time "O" .5 hr/1.25 hr Max Task Time "O" 1.0 hr./1.25 hr Mean Task Time "I" 1 hr/.966 hr Max Task Time "I" 2 hr/.9 hr	94 95
F-16 GTWT (APG-66)		781B LEVEL F (4.9 g RMS)	N/A	N/A
F/A-18 (APG-65)		781B	MTBUMA (FH) 40/- MTTR .20 hr/- DMMH/FH .26MH/	SEQ Plan
TPQ-37	AD LRIP XLRIP	- Tailored Tailored	MTTR(O-LEV) 30/ 27.5 Min MTTR(DS-LEV) 120/ 52 Min MAXTTR - /52 Min	
TPQ-36	ED PROD (FAT) PROD (1-4) PROD (5-7)	Tailored Tailored Tailored Tailored	MTTR(O-LEV) 30/ 14.5 Min MTTR(DS-LEV) 120/ 75.5 Min MAXTTR(O-LEV) 120/ 28.3 Min MAYTTR(DS-LEV) 240/145.4 Min	
LDNS	PROD	-	MTTR(O-LEV) 15/8.9 Min MTTR(I-LEV) 30/13.2 Min MTTR(D-LEV) 60/NT Min	-

- (1) SPECIFIED "θ<sub>0</sub>" MTBF/TOTAL TEST HOURS  
(2) F-15 USED NATURALLY OCCURRING INCIDENTS FROM 30 HOUR RELIABILITY TEST  
(3) REQUIREMENT/DEMONSTRATED  
(4) MODIFIED TO -40°C AND RANDOM VIBRATION  
(5) WAIVED BASED ON RESULTS OF THE F/A-18 RADAR 85 HOUR MTBF TEST (149 HRS & ZERO FAILS CORRESPONDS TO 106 HR θ<sub>0</sub>).  
(6) MODIFIED TO -40°C

FIGURE C-20. R&M Demonstration Tests

The F-15 case showed progressive MTBF growth thresholds (30, 45, 60) with demonstrations required to show attainment of the required thresholds. The case goes to considerable length to show the relationships of known/firm requirements, and demonstrations to building confidence in meeting user thresholds. The F-15 approach of creating a series of demonstrations, encouraging Failure Analysis and Corrective Action, and application to follow-on equipment and further demonstration, supports the value of demonstration testing.

The first 30-hr MTBF RQT was started in November 1973, 14 months later than originally planned, one year after Environmental Qualification Tests were initiated, and four months before they were completed. Factors also contributing to the delay in the start date were reassignment of RQT assets and difficulties with test chamber facilities. During early attempts to start, test facilities were less reliable than the radar being tested.

Planned start dates for the production reliability tests (PRT) covering the 45-hr and 60-hr test were also delayed by 15 months or more. These test schedule slippages were due, in part, to having only one test facility which became available only when each test was completed. Many of the delays involved the solution to software problems which held up conducting the test. Once the demonstration tests began they were successful. As of December 1982, no APG-63 radar had failed to pass its required reliability test (Ref. F-15 Case Study, pp. IIE-10 to IIE-52).

The F-15 radar case makes the statement: "It is inherent in MIL-STD-781 demonstration testing, which places a premium on measured MTBFs, that prime contractors and subcontractors will be concerned with passing tests. Since there is a financial cost and a matter of reputation associated with failure, it follows that test delays tend to be the result since these do not involve incentives or substantial penalties" (Ref. F-15 Case Study, p. IIE-11).

The TPQ-37 program began with no quantitative reliability requirement and therefore no contractor demonstration, just a MTBF goal of 250 hours. A firm MTBF requirement of 90 hours with a demonstration test was added to the LRIP contract. After incorporation of the demonstration requirement, the TPQ-37 experienced an abrupt increase in reliability emphasis and every part of the LRIP effort became potential input to a program to grow reliability. The demonstration requirement combined with an incentive provision resulted in growth from DTI/OT I MTBF of 24/45 hours, respectively, to an MTBF of 125 hours (Ref. FIREFINDER Case Study, pp. 164, 165).

The F/A-18 case study indicates that the 85-hour MTBF requirement (that for later units rose to 106-hour MTBF requirement) was in the minds of the program manager and motivated the development effort to produce a "106-hour radar," as was the M/BIT Demo requirement.

A Reliability Demonstration Test was performed on the LDNS during the development program to determine that the equipment design complied with the reliability requirement in terms of the specified MTBF of 1000 hours. The test was performed in accordance with Plan XXI of MIL-STD-781B. The total test time (equipment on) was 1840 hours with three failures occurring. This test was the only measure of acceptance for the reliability requirement.

A point is made in each case that very often insufficient assets are available during the development and preproduction phases. When this happens, engineering/growth/test events are strung out, valuable data are delayed and assets are sometimes submitted to conflicting environments (e.g., reliability tests and destructive/degrading tests using the same sample/item). Certain R&M development tests are cut out because the R&M sample is diverted to another purpose.

The cases studied indicate that, when properly applied, demonstration testing is a motivator to the contractor, and a useful tool for the procuring agency to gain assurance that the desired characteristics contracted for are inherent in the item.

R&M characteristics are not as obvious in a system as are other characteristics like weight, power, size, speed, etc. Reliability characteristics and to a lesser extent maintainability characteristics are dependent on factors such as the operational modes, mission profiles, environments and, of course, time.

The demonstration is a structured test in a controlled environment. The reliability or maintainability demonstration appears to be the best measure of the true reliability inherent in the system, other than the field use. The demonstration is, of course, the event at which government and management determine pass/fail, acceptability of design, LCC considerations, incentive payments, progress toward awards, and meeting established R&M thresholds.

A formal agreed-upon set of characteristics demonstrated in accordance with agreed-on definitions, conditions and standards appears to be supported by each study as desirable and essential.

#### 5. Operational Testing

Each case study discussed operational test in some form and emphasized the need to satisfy the user of the system. The cases report that every attempt must be made to bring the system up to or above the original requirement of the ultimate user. "Operational Testing" has many names (MTO&E, OT, Flight Testing, etc.), but each case emphasizes that the operational environment is "final true test" of the developed/produced system and new problems will be discovered which must be fed back into the system for corrective action.

#### 6. In-Service R&M Assessment

The ultimate demonstration of system R&M characteristics and their impact on readiness, mission capability, operating and maintenance costs, is after the introduction of the system into the operational units/force. Each of the cases presented included, in some form, a system for field R&M assessment and feedback into the corrective action/growth/maturation cycle.



The F-16 radar included an RIW contract with a specific turnaround time requirement. The F-16 case expressed the program's success measures in relation to field results attained, such as MFHBF of 65 hr, lower O&S cost, achieving predicted mature maintainability, fault-free radar flights, and an operational readiness exceeding 98 percent FMC. (Ref. F-16 Case Study, p. ID-3.) The LDNS was a RIW contract and reliability improvements similar to those experienced on the F-16 occurred after the systems were deployed.

The F/A-18 radar case study described the field reliability increasing throughout the period of 1980 to June 1982 to December 1982. The case study reports mean radar hours between removals as 14, 19 and 24, radar repairs as 27, 29 and 41, and primary failures as 42, 48, and 59 for the 1981, June 1982 and December 1982 reporting points, respectively. The case described in-service failure assessment as critical to R&M growth.

The F-15 case included extensive field reliability data, and credits the field data collection, failure analysis and corrective action/ECP system for the early and continuing growth of F-15 radar reliability.

The F-15 case makes a strong statement that comparing specification MTBF with field operational (AFM 66-1) reliability is expected to provide a 3-to-1 ratio. This serves to underscore the ever-present problem of comparing operational R&M requirements/measures/results with contractual specification requirements/measures/results (Ref. F-15 Case Study, p. IIE-56).

TPQ-36/37 mentions the fact that an attempt was made in those systems to create a common FD/SC and data collection technique. The FIREFINDER case study also brought out that the FIREFINDER Program Manager provided for field data collection and expects R&M improvement during the deployment phase of the system life cycle to be accelerated as a result (Ref. FIREFINDER Case

The FIREFINDER field data program was initiated in February/March, 1983, with trips to Fort Lewis, Washington, and Fort Hood, Texas. Preliminary field MTBFs have been established and changes identified in operational and maintenance procedures and technical manuals to improve the field R&M characteristics.

APPENDIX D

MECHANICAL WEAPON SYSTEMS ANALYSIS

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## APPENDIX D

### MECHANICAL WEAPON SYSTEMS ANALYSIS

Observations and analysis contained in this section are based on a review of the OSD/IDA R&M Case Study report for the T700 Engine (IDA Record Document D-22) and various other inputs on mechanical systems obtained as a result of presentations made to the R&M Core Group. The structuring in this section was derived from engine programs and, while it might be representative of a class of mechanical systems, it does not necessarily encompass all types of mechanical systems. For this analysis, the R&M program activities were divided into six major categories. They are: contracting, management, design, production, test and evaluation and observations. These six categories have been further subdivided into various elements similar to Appendix C.

#### A. CONTRACTING

The General Electric T700-GE-700 Gas Turbine Engine was developed under Contract #DAAJ01-72-C-0381 (52) with the U.S. Army Aviation Systems Command, dated 15 March 1972. The engine is the main propulsion system for the Army's newest utility helicopter, the Sikorsky-built UH-60A Blackhawk, with derivative models powering several other helicopters such as the AH-64 Apache and SH-60 Seahawk (Ref. T700 Case Study, p. I-2).

Line items in the contract specifically called out that a Reliability Program and a Maintainability Program be conducted in accordance with previously submitted program plans which had been reviewed and coordinated with U.S. Army planners well before award of the development contract (Ref. T700 Case Study, p. IIA-0).

## 1. R&M Requirements

Mechanical systems that are to meet successful levels of R&M require explicit definition in contractual documentation. Development of requirements for R&M can range from technology expressed as MTBF, MTTR, Shop Visit Rate (SVR), etc., to specifics, such as operating life of parts not easily accessible, level of skill required for maintenance actions, and types and numbers of tools required. Accomplishing adequate and understandable requirements is a function of the system and its defined mission.

In both the Prime Item Development Specification (PIDS), and in the separate R&M Program Plans, both quantitative and qualitative requirements were specified which were contractual requirements (not goals) to be demonstrated by the end of the development contract. They were:

Reliability Requirements: The engine shall achieve the specified reliability value of 1200 hours Specified Mean-Time-Between-Failure based upon decision risks of 10 percent and a discrimination ratio of two to one (Ref. T700 Case Study, p. IIA-16).

Engine Design Life Requirements: The engine shall have a design life of 5,000 hours, with an initial target of 1,500 engine operating hours MTBFRO (Mean-Time Between Failure Requiring Overhaul) at completion of the Post Qualification Reliability Demonstration Test Program (Ref. T700 Case Study, p. IIA-16).

### Maintainability Requirements:

- Corrective Maintenance - field levels - .07 mhr./op.hr.
- Preventive Maintenance - field levels - .03 mhr./op.hr.

- Total Direct Maintenance - all levels - .24 mhr./op.hr.
- Mean-Time-Between-Maintenance (MTBM) - 220 engine operating hours (excluding daily inspection).
- Mean-Down-Time - field levels - 1.7 hours.
- Active Elapsed Time to repair a Class V failure - 3 hours repair or servicing.
- All organizational repair or servicing maintenance - 30 minutes.
- All organizational and direct support maintenance procedures shall be capable of performance in Arctic clothing at -54°C without degrading the mean elapsed time by more than 50 percent.
- The remove/replace, total and elapsed times and special tool requirements were presented in the proposal and subsequent specification for:
  - All Modules (4)
  - All Line Replaceable Units (LRU's) (19)
  - Power Turbine Module Components (10)  
(Ref. T700 Case Study, p. IIA-10)

a. R&M Contract Goals Versus Requirements. Unless as high a priority is given to R&M as is given to the other factors of contracted requirements, a satisfactory R&M product will very likely not be achieved. The case studies demonstrated this

most clearly. Hard, well-defined requirements, rather than goals, are important. Requirements should be expressed in terms that can be translated to design factors such as accessibility, specific operating lifetimes of key components known to be high failure, and high cost items. In defining requirements the test of the user is the area of greatest challenge and must be dealt with carefully.

b. Defining R&M Requirements. To define the requirements, the needs of the customer must be well-understood. Lessons learned in Vietnam were used as a basis for setting R&M requirements. This established a need for significantly improved engine reliability and easier flight line maintainability. Examples of requirements not previously specified in engine developments were: (a) inclusion of an inlet air particle separator as an integral part of the engine (for protection against sand and dust damage) and (b) a low-cycle fatigue test requirement to ensure long life in the cyclic nature of helicopter engine operation.

## 2. Mission Profiles

To establish the life requirements of an aircraft gas turbine engine such as the T700, it is necessary to define the predicted mission usage in terms of percent of operating time at various power settings (stress rupture life) and the required low-cycle fatigue life. With these requirements established, the design engineer can then define his or her assigned component design to meet these criteria. As easy as this may sound, defining realistic mission requirements in advance of actually fielding the system is a very difficult task. If the time at maximum power, for example, is overstated significantly, then parts may be overdesigned which can affect cost and weight. If, on the

other hand, mission requirements are underestimated in the PIDS, certain parts might fall short of meeting the stated overall life requirements which could require costly redesign at a future point in time.

In the PIDS, the Engine Design Life Requirement was defined in the classic terms of percent time at a designated power level. This in effect defined a mission usage profile and was the original basis for designing the various engine components to meet a 5000-hour minimum life. This power spectrum profile coupled with the low-cycle fatigue requirement of 15,000 cycles, provided the original mission profile for the T700-GE-700 engine design (Ref. T700 Case Study, p. IIA-22).

### 3. R&M Failure Definition

The failure definitions used were not far different from those used in other case studies. The excluded failure categories were:

- (a). Failures resulting from errors of maintenance personnel.
- (b). Failures resulting from operating the engine beyond specification limits. Included failures are those operationally related failures for which engine provides integral protective devices (overspeed, overtemperature, hot starts).
- (c). Failures resulting from airframe components.
- (d). Failures to start, if a successful start is accomplished without corrective maintenance action.



- (e). Reported operating malfunctions which cannot be verified by subsequent investigation, flight or ground test.
- (f). Multiple part removals and other maintenance actions performed upon the same engine following an initial failure requiring maintenance action will be counted as one failure against the engine.
- (g). Failures of equipment not furnished by the Contractor.
- (h). Failures for which a corrective engine design change or an operational procedure change has been demonstrated, and approved by the Government, will be removed from the failure count, unless the events are identical to those for which corrective action was taken and it has been determined that the prescribed corrective action procedures have been utilized.

(Ref. T700 Case Study, p. IIA-18).

Failure classifications which related the severity of failures were:

Class I - Failures that result in destruction of an engine or loss of aircraft control or fire external to the engine.

Class II - Failures which result in In-Flight shutdown (i.e., unrecoverable power loss).

Class III - Failures which result in potential power losses completely or partially rectified by automatic or manual corrective action.

Class IV - Failures which result in power loss or no start.

Class V - Failure which requires unscheduled maintenance.

(Ref. T700 Case Study, p. IIA-A)

#### 4. Incentives

R&M contract incentives can aid in developing reliable and maintainable systems by focusing contractor management attention on actions that improve and ultimately meet or exceed specified requirements. The T700 program contained incentives that were successfully implemented to the contractor's and the government's benefit. The RIW (Reliability Improvement Warranty) played an important role in this program. During the first three years of production, General Electric produced the T700 under a warranty incentive agreement. The warranty agreement broke down into three segments. GE had to absorb 100 percent of the cost of repairing engines or components that failed during the first 250 operating hours; GE and the Army shared the repair costs for failures between 250 and 500 operating hours. GE incentives involved cost avoidance up to 500 hrs between unscheduled maintenance with a positive cash flow increasing linearly from 500 to 750 hrs. (See Fig. D-1) It obviously was very much in GE's interest to produce problem-free T700 engines.

Early production or start-up problems turn up in every new production engine and the T700 was no exception. A couple of problems developed which had to be corrected, the most significant being the number four bearing support bottoming in the midframe, thereby negating the effect of the bearing support oil film damping feature. The warranty provisions of the contract enabled

GE to move quickly and successfully to solve the problem. Approximately 90 percent of the shop visits in 1979 were removals to correct this discrepancy plus one or two other start-up problems.

It is believed that the warranty incentive provided a big payoff for the Army because it hastened early solution to start-up production problems and accelerated achieving a mature engine. The Army elected to discontinue the warranty after three years of production (Ref. T700 Case Study, p. II. C-105).

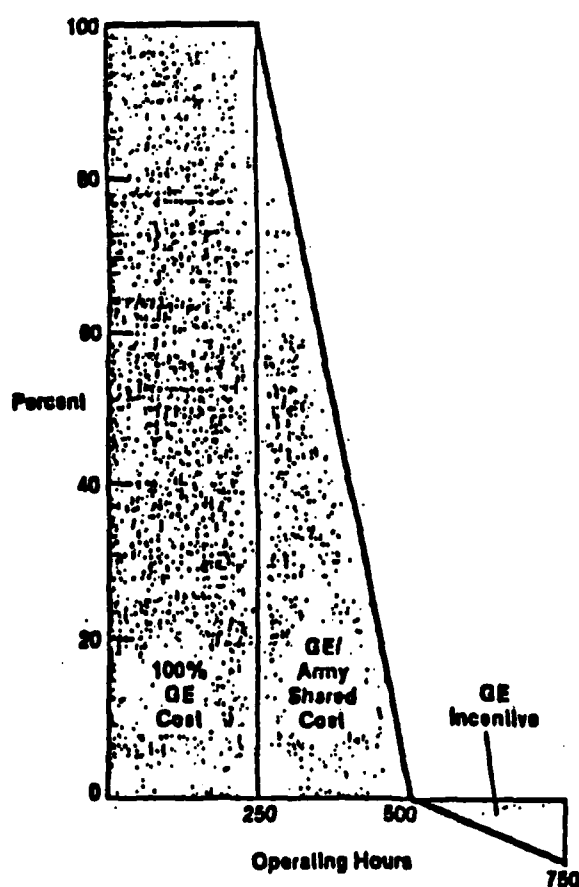


FIGURE D-1. T700 Warranty Incentive

## 5. Source Selection Criteria

In the cover letter of the Official Request for Quote (RFQ), #DAAJ01-71-00455(52), which was issued to General Electric, Pratt and Whitney and Lycoming in July, 1971 for the development of a 1500-shaft-horsepower turbine engine, the following statement appeared in the block entitled, "ITEM(S) TO BE PURCHASED (Brief Description).

"Design, develop, fabricate, test, demonstrate reliability and maintainability and qualify a 1500-shaft-horsepower, non-regenerative, direct front drive, turboshaft aircraft gas turbine engine for the Utility Tactical Transport Aircraft System (UTTAS)."

The theme of this brief description was carried throughout the entire RFQ, leaving no doubt that the U.S. Army was very serious about R&M being of prime importance on this new engine.

Under Section D of the RFQ the Evaluation Factors were defined for making the award of a contract as a result of this RFQ. In paragraph D.5, three major evaluation elements were delineated with the possible points to be awarded for each of these elements as follows:

<u>EVALUATION ITEM</u>	<u>POSSIBLE POINTS</u>
Technical	700
Management	150
Cost	150

Under sub-paragraph D5.1 Technical, sub-paragraph D5.1.1 breaks down the elements for the evaluation of the design and performance of the engineering and logistical critical components.

This statement points out that specific attention should be given to the following items:

- 1) Systems Design
- 2) Component Design
- 3) Trade-Off Analysis

Items of the System Design will include:

- 1) Sub-system Development
- 2) Configuration/Weight Analysis
- 3) Performance/Power Extraction
- 4) Operating Limitation
- 5) Reliability and Maintainability
- 6) Systems Integration
- 7) Materials
- 8) Vulnerability and Serviceability
- 9) Producibility/Production Margins
- 10) Condition Monitoring
- 11) Diagnostics

It may be noted from this set of evaluation criteria that Reliability and Maintainability were given careful consideration with other engine characteristics such as performance and weight. There has never been any question from the very beginning of this program that Reliability and Maintainability were given very high priority in the selection of this new Army helicopter engine (Ref. T700 Case Study, p. IIA-70).

## B. MANAGEMENT

Because success in R&M for programs with mechanical systems involves assurance that R&M factors carry equal billing with the other program elements, it is necessary that management overview of R&M be emphasized. In the T700 program, maintainability and reliability were given the highest consideration, and this priority was clearly conveyed to the competing contractors. As a result of this emphasis, the correct levels of planning, control and emphasis were established at the prime level, subcontract level, and vendor level.

### 1. Planning, Control and Emphasis

The organizational structure is the key to meeting the planning control and emphasis of R&M. R&M cannot be treated as a minor element on a program. The case studies conducted strongly support the idea of a separate R&M manager and R&M support personnel integrated with engineering, configuration control, etc. The relationship with the other elements must obviously be very intimate, and adversary relationships have to be avoided. It is the responsibility of the program manager to see to this since a breakdown here will destroy the probability of a successful R&M effort. In the T700 engine RFQ the Army specified that the R&M, Safety and Human Factors Engineering Manager report to the Project General Manager at the same reporting level as the Design and ILS managers (Ref. T700 Case Study, p. IIB-4). Strong and understandable planning documents must be prepared and adhered to. Coordinated efforts must be orchestrated properly. Milestone charts, PERT charts, road maps, or whatever one may wish to call them need to be used to ensure that R&M effort maintains a course to successful integration.

## 2. Monitoring and Control of Subcontractors and Suppliers

As important as the above is to the prime contractor's efforts, the same concept must be applied to subcontractors and vendors. Monitoring and control efforts must be established to accomplish these tasks. The key factors to accomplish this, found in the case studies, included R&M factors clearly spelled out in RFQs, clear and precise detailing of R&M factors in program plans, contractual requirements agreed to and understood between prime and sub, and equal emphasis applied. Monitoring required proper reporting to the prime, in-depth reviews, and adequate screening of sub-supplied hardware (Ref. T700 Case Study, p. IIB-22).

## 3. Engineering Change System

It is important to avoid delays in the incorporation of ECPs found necessary to ensure good R&M, and to review other changes to make sure R&M has been properly addressed. The review and development of change documentation must be done with the same care as the initial program when being contracted. Unnecessary delays in the approval cycle must be avoided and the incorporation must be such that the disruption to the progress of the program is held to a minimum.

The T700 case study verified this concern and demonstrated its importance. In the maintainability and mechanical areas, one of the key elements was flexibility in processing changes. As stated in a GE briefing, the T700 Engine Success Story, "the ECP process was as flexible as it could be, which allowed the contractor to recognize and correct problems as quickly as possible." During the first three years of production of the T700 helicopter engine, General Electric was under contract to provide total contract support which provided the contractor with full configuration control and logistics support flexibility. This contract

provision and a reliability improvement warranty agreement gave General Electric the latitude and incentive to rapidly correct R&M problems and introduce fixes throughout the fleet. Planning and control and monitoring played a large and important role in this area.

It should also be noted that relatively few ECP's have been necessary for the T700, a fact that many believe to be the result of a successful maturity period after completion of FSD and prior to production.

### C. DESIGN

The fact that an engine has a very large number of failure modes due to the nature of the hostile operating environment and the drive to design lightweight efficient structures requires particular attention to R&M in the design process. Thermal and mechanical stresses are very high and minimal weight is a paramount design consideration. The aerodynamic, mechanical, structural, combustion/heat transfer, fuels/lubricants, vibratory, controls, etc., disciplines are severely challenged in this design process. With increasing application of electronics in the engine controls area, a significant challenge exists there too, in order to ensure reliable operation of electronics in a high temperature, noise, vibratory, and "g" loading environment. This section presents these issues as derived from the General Electric T700 Case Study and the USAF's Engine Structural Integrity Program as applied to the F100 and F101 engines.



## 1. Development of Design Requirements

Achievement of a truly reliable and maintainable engine required a consistent high priority approach from the Army and General Electric, using the lessons learned from past experience. Fig. D-2 summarizes the Army's late-1960 Engine Experience.

U.S. Army Concept Formulation studies for replacement of the UH-1 transport helicopter began in the mid-sixties and resulted in a system called UTTAS (Utility Tactical Transport Aircraft System). This system had some challenging requirements such as:

- 37% - 50% reduced maintenance man hours
- 20% - 30% reduced fuel consumption/engine
- Improved survivability
- 1,500 shaft horsepower
- Integral engine protection against sand and dust
- Reduced logistics support.

The Army sponsored a successful *four-year* Advanced Technology Engine (ATE) competitive demonstration program with General Electric and Pratt and Whitney which substantiated that the performance requirements were achievable in a full-scale development program. During the latter period of the ATE demonstrator program, Army and GE R&M engineers conducted an in-depth review of the current Army engine experience and postulated about the future operational and maintenance environment, from which the design requirements were developed (Ref. T700 Case Study, p. IIC-6).

# Late 1960s Engine Experience

## Reliability Characteristics

- 600-1,200 Hour TBO Due to Compressor and Turbine
- 600-900 Hour Hot Section Maintenance Interval (Combustor)
- High Shop Visit Rate to Intermediate and Depot
  - 0.5 Mechanical Failure
  - 0.4 FOD
  - 0.3 Improper Maintenance
  - 0.2 Scheduled (TBO)
  - 0.2 Seal Leakage
  - 0.1 Erosion
  - 1.3 Other (Airframe, Convenience Operator, Unknown)
- 3.0 Total SVR

## Maintainability Characteristics

- Complicated Rigging of Fuel Control
- High Maintenance Induced Failure Rate
- Accessibility Often Difficult
- Time Consuming Safety Wiring
- High MMH Burden for Hot Section Replacement



Ref: USAAMRDL TR 73-28

FIGURE D-2. Late 1960s Engine Experience

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ENSIP or Engine Structural Integrity Program is a formalization of the structural design and demonstration approach which the Air Force has developed from lessons learned from the TF30, TF34, TF39, TF41, F100, F101, F107, J85-21, and YJ-101 engine programs, as well as others.

Figure D-3 categorizes failure mechanisms for various types of engine structures. Some structures exhibit more than one failure mechanism. For instance, turbine blades fail in stress rupture, high-cycle fatigue and low-cycle fatigue. Since turbine blades operate with centrifugally-induced stresses of 30,000 g's or better, as well as high thermal stresses from operating in 2000-3000°F gas temperatures, while cooled with 1000°F cooling air, and under high aerodynamic loads as well, one can see the challenge of the structural designs for these essentially thin-walled shells transitioned from relatively heavy platforms.

<u>COMPONENT</u>	<u>TYPICAL MECHANISM</u>	<u>DESCRIPTION</u>
FRAMES CASES ➡	LOW CYCLE FATIGUE (LCF)* ➡	CRACKING DUE TO REPETITIVE APPLICATION OF CENTRIFUGAL LOADS, APPLIED PRESSURES, THERMAL STRESS AND/OR FLIGHT LOADS
BLADES, DISKS BEARINGS ➡		
VANES THIN SHELL STRUCT. ➡	HIGH CYCLE FATIGUE (HCF)* ➡	CRACKING DUE TO HIGH FREQUENCY STRESS OSCILLATIONS CAUSED BY AERODYNAMIC, SONIC, OR MECHANICAL VIBRATORY EXCITATION FORCES
TURBINE BLADES ➡	STRESS RUPTURE* ➡	DEFORMATION & CRACKING DUE TO PROLONGED APPLICATION OF LOAD AND TEMP.
VANES NOZZLES AUGMENTOR LINERS ➡	OVER TEMP (BURN-THRU) ➡	LOCAL MELTING DUE TO EXCESSIVE TEMP.

\* PRE-EXISTING AND/OR SERVICE INDUCED DEFECTS CAN ACCELERATE CRACKING

FIGURE D-3. Engine Structural Failure Modes--Typical Structural Failure Mechanisms

Army planners placed reduction in maintenance and logistics support requirements as the major technical goal, from which three primary design requirements evolved:

- Design for "On-Condition" Maintenance
- Apply State-of-the-Art Technology to Improve Reliability
- Make Maintainability a Primary Design Consideration.

Army R&M Engineers prepared the qualitative and quantitative Reliability and Maintainability requirements and objectives for UTTAS engine development for the Prime Item Development Specification (PIDS). These "R&M" requirements represented the best ideas collected from experienced specialists in Industry and the Military. General Electric Company translated the requirements to its engineering organization in terms directly related to specific, significant consideration that would impact the design, such as:

- A rigid set of rules limiting and controlling the use of lockwire.
- All installation and module replacement to be accomplished with only 10 of the 182 hand tools in the A07 Army tool Box.
- The engine design would not require any special tools at Aviation Unit Maintenance (AVUM) or Aviation Intermediate Maintenance (AVIM) levels.
- When oil level reading is low, the oil tank will always accept a complete quart without detrimental effect.
- The engine would require no adjustments or trimming at the field maintenance level for any reason.
- Mount locations would not interfere with installed module replacement.
- No loose balance weights to be exchanged during module replacement.

(Ref. T700 Case Study, p. IIC-8).

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## 2. Design Alternative Studies

Design trade-off studies were utilized to optimize the design from the standpoint of meeting all of the T700 gas turbine engine requirements. The resulting changes substantially improved the R&M of the engine. Some of the more significant trade-off studies were:

a. Integral Inlet Particle Separation. In the past, turbo-shaft inlet separators were provided principally as airframe parts of the total installation. General Electric's experience with inlet separators in its T58 and T64 engine installations indicated that separators could be most efficiently designed as part of the engine (Ref. T700 Case Study, p. IIC-16).

b. Top Mounted Controls and Accessories. Studies showed that accessibility and ease of maintenance were significantly enhanced by top mounting the accessories and accessory drive. This also provides protection from small arms fire (Ref. T700 Case Study, p. IIC-18).

c. Axial-Centrifugal Compressor. Numerous design trade studies were made on the optimum compressor configuration to be pursued for the next generation of helicopter engines in the 1500 SHP class, which led to the combination of the axial-centrifugal design of the T700 compressor.

Another trade-off design study was conducted on replaceable compressor blades in the axial stages versus the 'blisk' design in which the blades are machined into the wheel. The decision was to go with the "blisk" construction. The T700 axial compressor design evolved with only 11 major parts (Ref. T700 Case Study, p. IIC-20)

d. Combustor. Conventional combustors of the 1960s were, for the most part, fabricated shells with duplex vaporizing fuel nozzles which had poor durability. A more expensive machined ring design, incorporating central fuel injectors with better durability, provided a much lower LCC than the lower cost fabricated design (Ref. T700 Case Study, p. IIC-22).

e. Gas Generator Turbine. A more complicated turbine blade cooling scheme was rejected in favor of maintaining the simple and more reliable radial convection system (Ref. T700 Case Study, p. IIC-24).

f. Power Turbine. Simplification reduced the number of parts and material provided substitutions payoffs in cost, R&M, life and engine weight (Ref. T700 Case Study, p. IIC-24).

g. Bearing and Lube System. A six-bearing configuration (two on the gas generator and four on the power turbine) was selected as providing the optimum balance of rotor dynamic stability, ease of assembly and durability (Ref. T700 Case Study, p. IIC-26)

h. GE12 to T700 Design R&M Requirements Drove the Design of the T700 Engine. Early in the program, the Army awarded a supplemental contract to the T700 contractor to perform a Maintainability Demonstration/Reliability analysis on the demonstrator engine. This work pointed out several areas where maintainability improvements were required in the design.

During the GE12 (ATE) demonstration in early May 1971, for example, excessive times to remove and replace the fuel controls were experienced in addition to numerous hand tools and several special tools being required to remove and replace the combustion liner. The T700 engine was completely redesigned to remedy the

identified Qualitative and Quantitative problems. A "module" concept was adopted to allow replacement of entire subsystems with a minimum of time and mechanical expertise without the need for special tools. The assembly and disassembly of modules has been simplified for easier, quicker and more error-free maintenance (Ref. T700 Case Study, p. IIC-28).

### 3. Design Evaluation Analysis

On the T700 program, R&M analyses were required by the RFQ and delineated in the R&M program plans. They were performed as an on-going process in conjunction with design. These analyses resulted in several design changes and were considered a very valuable tool in attaining R&M objectives (Ref. T700 Case Study, p. IIC-36).

Computerized design evaluation analyses were used to track and predict engine reliability and maintainability of the T700-GE-700. Important mechanical and thermal stress analyses were also used to develop higher reliability. These types of evaluation analyses are also required for ENSIP Task II.

Reference paragraph 7, below, for CAD systems used in the T700 program.

### 4. Parts and Material Selection and Control

Parts and material control was the responsibility of the designer under the cognizance of the reliability manager for the T700-GE-700 engine. This resulted in parts and material control which was optimized between performance and reliability. A number of special design considerations were introduced into the General Electric engine design to provide a marked increase in engine reliability when compared to previous engine designs. Some of the more significant items are:

a. Combustor System

- Casing made from INCO 718 for strength and corrosion resistance.
- Machined liner, giving low stress concentration and less susceptibility to cracking.
- Constructed from Hastelloy X, the T700 combustor system is designed to have a minimum life of 5000 hours when operated at rated temperature levels at a representative helicopter loading schedule. Within this life, 10,000 start-stop cycles are allowed to account for cycling during the mission. Thus, the total low-cycle fatigue life is designed to be not less than 15,000 cycles.

(Ref. T700 Case Study, p. IIC-42).

b. Turbine Blades

- The turbine blades are precision castings of R120 material with a nickel-aluminide diffusion coating. Rene 120 was selected because it offers the best balance of capability in terms of rupture life and cooling flow. R120 is already in development production for General Electric's F101 and J101 engine hardware.

c. Nozzles

- The Stage 1 nozzle is an investment casting of X40, an alloy which has a long history of successful casting. Stage 2 nozzles are investment cast in segments of two nozzles each in R80 material. The 100 percent rated speed at SLS, STD is 44,720 RPM. The rotor system has been designed to meet fully the overspeed



requirement of 115 percent of maximum rated  $N_G$  limit, plus ample margin for burst (15 percent more).

d. Power Turbine

- High strength shaft made from INCO 718.
- Integral bucket tip shrouds provide vibration damping.
- Designed for 5,000-hr life.  
(Ref. T700 Case Study, p. IIC-44).

e. Bearings and Lubrication

- Bearings are made from M50 material with dual oil jets and positive locking on inner and outer races.
- Size of No. 3 bearing was increased to provide longer life from YT design.
- All main shaft bearings have oil squeeze film to dampen rotor vibration response.
- Filter system has 3-micron element and impending bypass and bypass indicators. The capacity of filter was more than tripled (.6 square feet vs. 1.895 square feet) to extend service life.

(Ref. T700 Case Study, p. IIC-44).

f. Miscellaneous

- Electrical connectors are hermetically sealed. Critical connectors have been made "scoop-proof" by extending the shells, which prevents bending of the pins when being mated.

- Hydromechanical unit has torque motor with redundant windings.
- Ignition exciter has redundant circuitry.
- Ignition system has redundant igniters and power is engine-supplied.
- System has seven 2-element probes to provide thermocouple redundancy and the immersion depth was changed for improved temperature measurement accuracy and control.

(Ref. T700 Case Study, p. IIC-46)

## 5. Safety Factors

The design of the T700-GE-700 engine and the selection of materials included safety factors, i.e., margins over rated requirements. Some of these were:

- The frame struts are designed to favor 60 percent power condition with minimum chord to minimize losses during off-design high swirl conditions.
- Power turbine life is 5000 hours including 750 hours at 100 percent intermediate rated power and with 15,000 cycle minimum low-cycle fatigue life.
- The turbine has a minimum overspeed margin of 115 percent of maximum rated speed limit.
- Rugged torque shaft replacing bell cranks and actuator is integral with the HMU. Stall margin has been increased by lengthening the Stage 1 compressor blades by 0.025 inch and by aerodynamic redesign of the centrifugal impeller and diffuser.
- Combustor designed for 5,000-hr life.

The ENSIP's Task II requires that stress concentration factors be considered as a design variable. Figure D-4 illustrates the effect on life with the use of different stress concentration factors. There were no exceptions to safety factors in the T700.

## 6. Thermal Criteria

Temperature effects are the major drivers of turbine blade and vane life considered in the design of the combustor, because an undesirable temperature profile out of the combustor can put maximum thermal stress at the root area of a turbine blade, where mechanical stresses are high due to centrifugal, bending torsional, etc. The desired temperature profile places highest thermal stresses in the area desired. The combustor structure itself must be lightweight, require minimum liner cooling and, although a static structure, it must withstand large and often transitory thermodynamic and mechanical stresses.

Modern turbine vane design has been developed which alleviates the major problem of leading edge cracking and hot gas ingestion with subsequent oxidation and failure which cannot readily be overcome by material selection alone. Positive  $\Delta P$  through the leading edge compartment provides out-flow even under cracked conditions and prevents oxidation with resultant extended life. The ability to cool hot section parts with an absolute minimum use of cooling air is the challenge compared to those previously discussed for the combustor (See Fig. D-5).

Figure D-6 shows the sensitivity to dwell effects of the F100 first stage turbine disk. The figure emphasizes that the temperature effects due to dwell of as little as 30° to 50°F can result in loss of 1000 cycles in disk rim life.

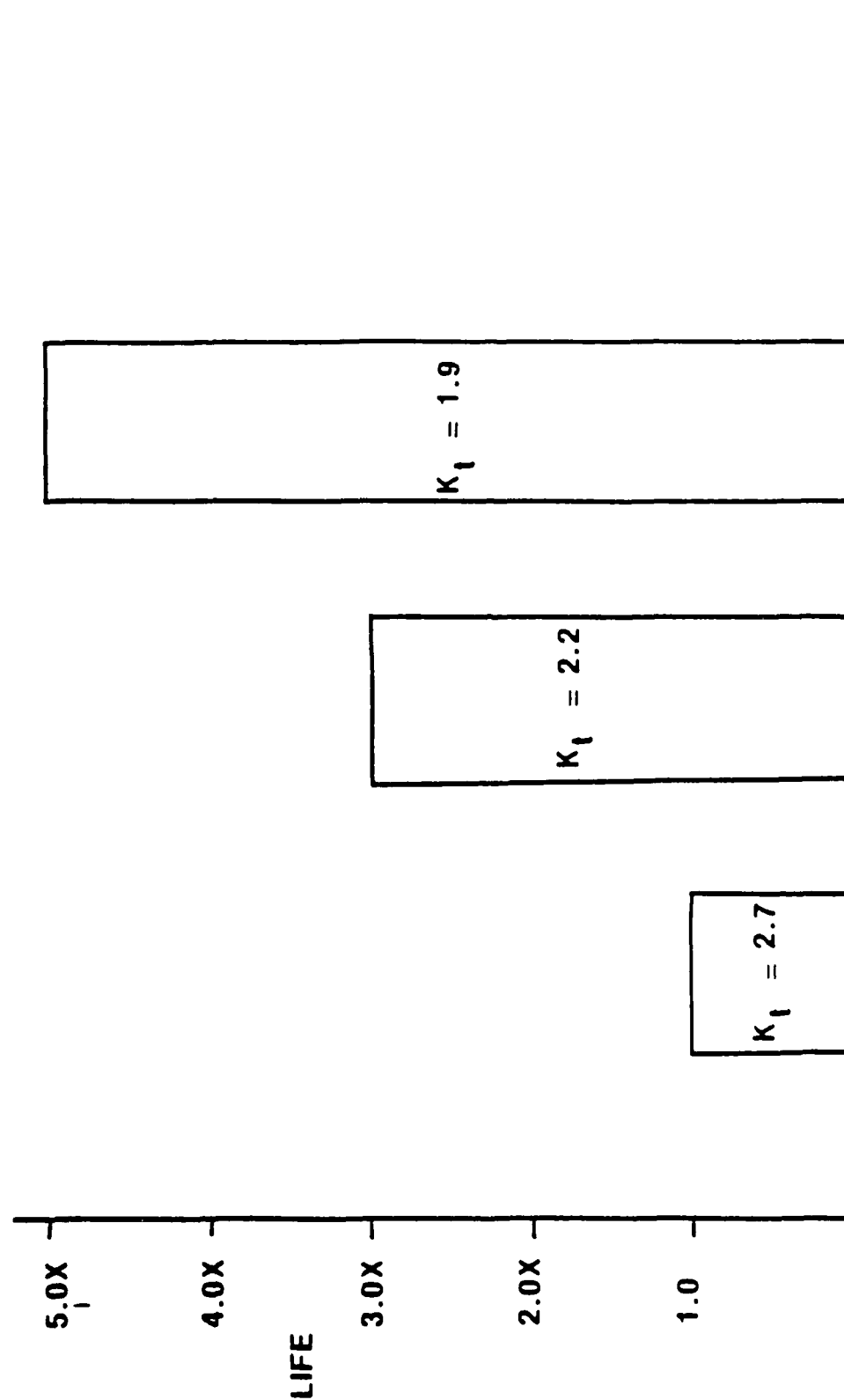
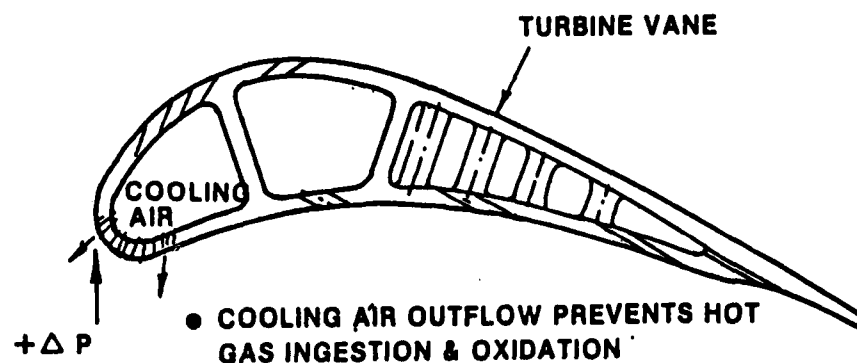


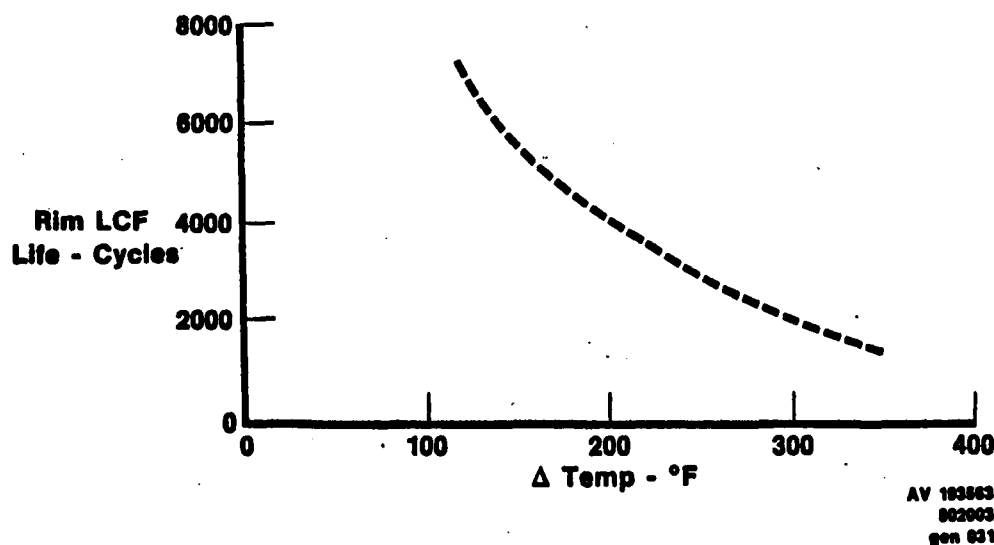
FIGURE D-4. Design Variables--Life Versus Stress Concentration Factor ( $K_t$ )



**DESIGN CONCEPT USE ON:**

- TF34 (A-10)
- F101 & F101 DFE
- F100 ILC
- TF41 (A-7)

**FIGURE D-5. Design Variables--Dual Compartment Positive Outflow Vane**



**FIGURE D-6. First Turbine Disk is Significantly Affected by Idle Dwell Time**

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## 7. Computer-Aided Design

Computer programs were utilized in numerous ways in the design and R&M areas to assist the engineers in performing analyses and design studies which contributed to the success of the T700-GE-700 engine in the areas of reliability and maintainability. The following are some of the computer programs which were used:

- Axial compressor airfoil generation including templates for manufacturing
- Centrifugal compressor aerodynamic configuration
- Turbine airfoil generation
- Aeromechanical blade analyses
- Heat transfer analysis
- Rotor dynamics
- Structures analyses
- Control system/airframe rotor system dynamic simulation
- Performance decks at various operational conditions.

During the course of the Development/Qualification Program, many computer-aided design (CAD) tools have been put into place at the Lynn, Massachusetts operation, and gradually, items such as the clearance drawing for the engine have been computerized, through the advanced interactive graphics system, so that stack-up checks may be performed when flow path changes are made to show the design engineer the impact of such changes on adjacent engine components.

During the development of the final MQT design for the power turbine, High Energy X-ray (HEX) pictures were taken on an actual operating T700 development engine at the General Electric outdoors testing facility at Peebles, Ohio. These X-rays were used in conjunction with interactive graphics to establish the tip clearances and shroud configuration for the MQT design power turbine.

In the area of reliability, a computer math model called "BRACE" was employed for assessing/predicting the reliability Mean-Time-Between-Failure (MTBF) for the T700 engine at any point in time. All failure data/corrective action experience was input to this program so that a current MTBF prediction was available at all times.

In a similar manner, a Maintainability Math Model ( $M^3$ ) was employed which showed the relationships between components, parts and maintenance procedures and calculated quantitative maintainability values.

At the conclusion of the MQT program, and during the transition from development to production, a Producibility Engineering Planning (PEP) program was put into place to "productionize" the manufacture of the various components for the T700 engine. As a result of this effort, much of the engine was programmed onto tapes for manufacture via numerically-controlled machines. This assured a much greater part-to-part repeatability and much tighter control of design tolerances, resulting in better overall reliability (Ref. T700 Case Study, p. IIC-50).

The Air Force also used computerized techniques for analyses and design aids such as fatigue design. Figure D-7 shows a level of detailed analysis around holes and slots in a typical rim. By careful analysis and design iteration, stress levels and concentrations can be controlled. For instance, after initial design and analysis of this part, it was redesigned to include additional slots rather than holes, thus reducing the relative local stress levels while equalizing the loading across the part. Figure D-8 depicts the ability to do sophisticated stress analysis. It is, of course, critically important to know the environment accurately as a basis for this analysis.

Figure D-9 shows the extent of the analysis that can now be performed with the capabilities of analysis, instrumentation, and test techniques now available. The use of eddy current

techniques in this case resulted in design of several new probes, as well as automated techniques for probe scanning and recording. This capability is used throughout the industry.

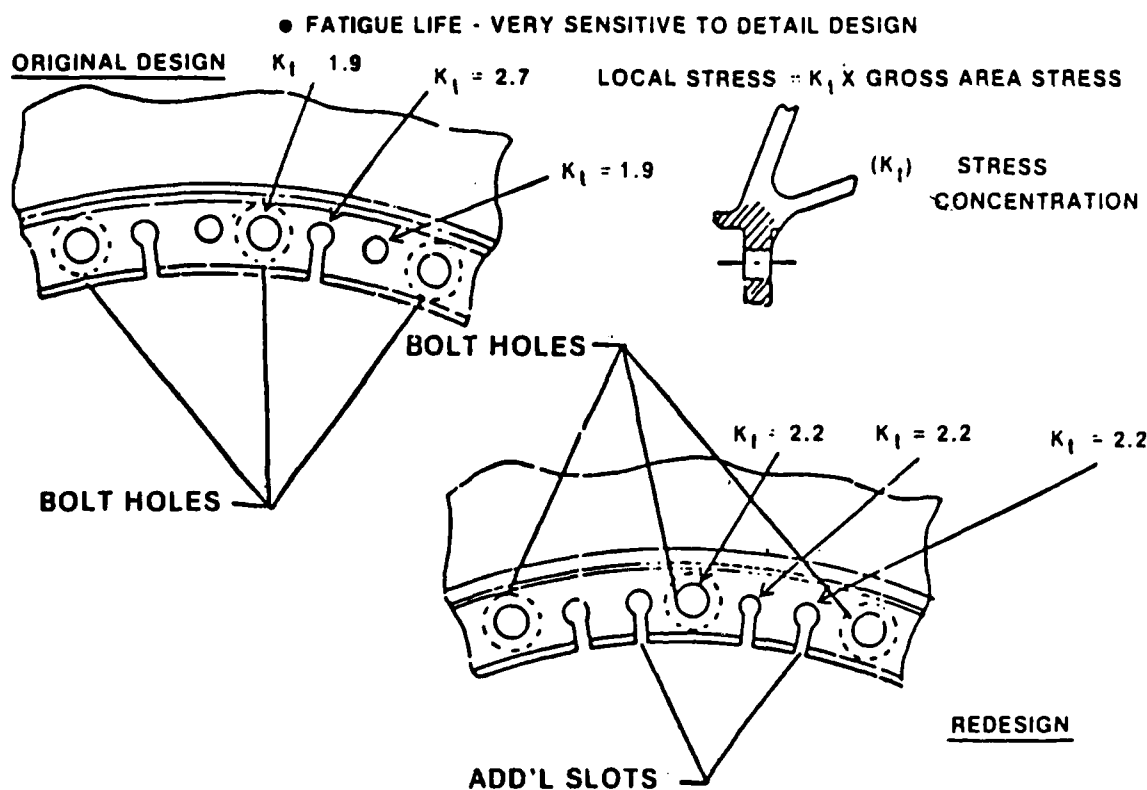
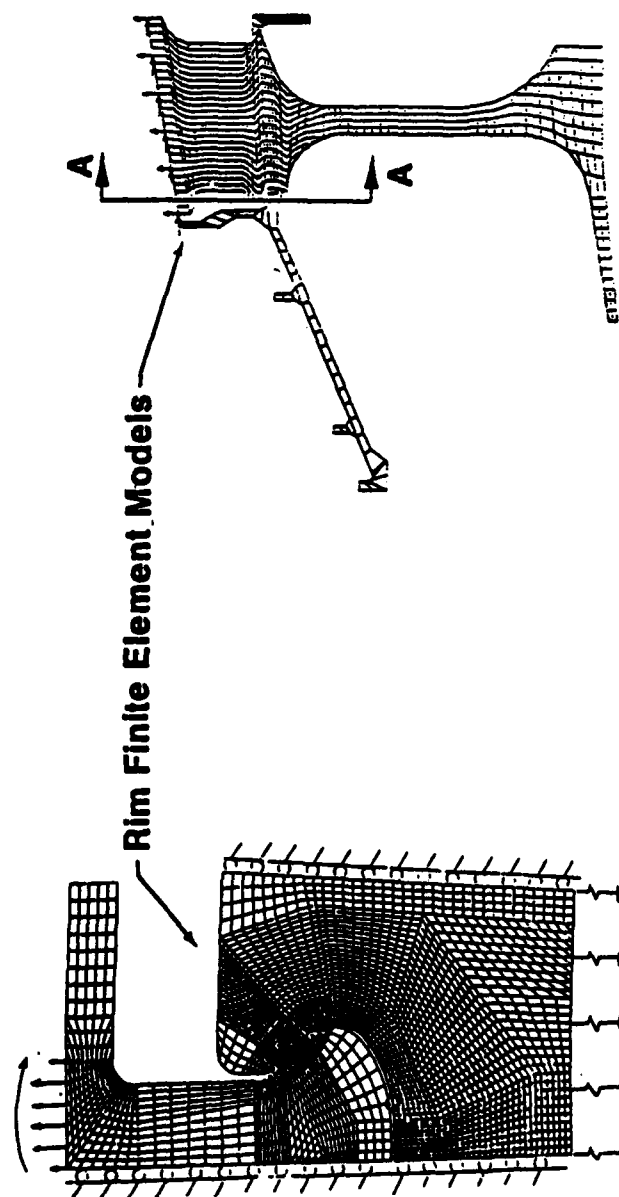


FIGURE D-7. Design Variables--Fatigue Design





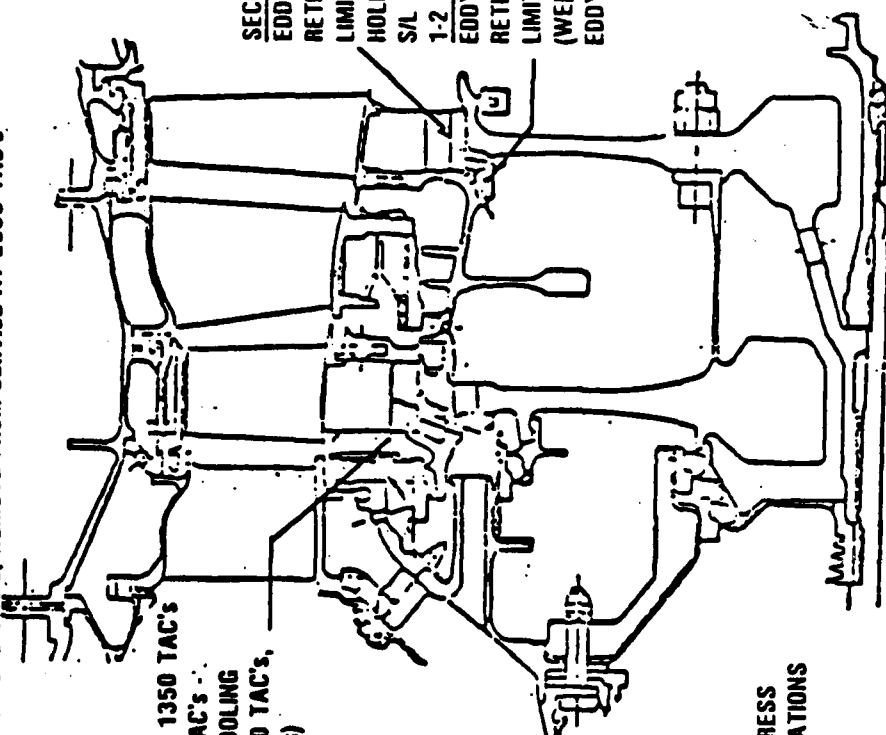
• Finite element analysis on many high stress locations

• Disk/shell analysis for nominal stresses

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FIGURE D-8. Typical Disk Stress Analysis

INITIATION LIVES AND SAFETY LIMITS ALLOW OPERATION PER CURRENT SCHEDULED MAINTENANCE INTERVAL  
INSPECTION BY 1350 TAC's; REMOVE FROM SERVICE AT 2300 TAC's



FIRST DISK  
EDDY CURRENT AT 1350 TAC's  
RETIRE AT 2300 TAC's  
LIMIT IS RADIAL COOLING  
HOLE (LCF = 1700 TAC's,  
S/L = 1400 TAC's)

SECOND DISK  
EDDY CURRENT AT 1350 TAC's  
RETIRE AT 2300 TAC's  
LIMIT IS RADIAL COOLING  
HOLE (LCF = 1600 TAC's,  
S/L = 1500 TAC's)

1-2 SPACER  
EDDY CURRENT BY 1800 TAC's  
RETIRE AT 2300 TAC's  
LIMIT IS AFT COOLING HOLE  
(WEB COOLING HOLES REQUIRED)  
EDDY CURRENT AT 1350 TAC's

\*SPIN TEST IN PROGRESS  
TO VERIFY CALCULATIONS

FIGURE D-9. F-15 Mission Re-analysis for High Turbine

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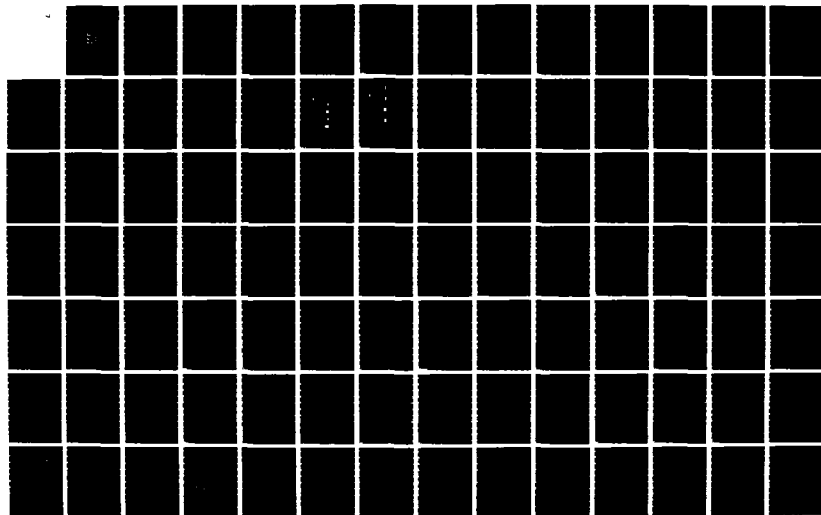
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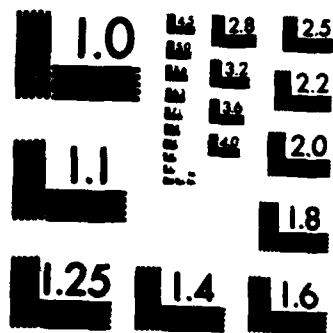
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MICROCOPY RESOLUTION TEST CHART  
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## 8. Testability Analysis

The T700-GE-700 engine required an on-condition monitoring and diagnostic system. The requirements for the design features to effect that capability were part of the maintainability requirements given to the designers. The maintainability analysis assessed and documented the fault isolation capability of the on-condition monitoring.

## 9. Testability Verification and Testing

The T700-GE-700 engine was designed for operation in an environment that is both hostile and geographically far removed from home base. Due to the high reliability demonstrated by the T700-GE-700 engine, only a 10-hr inspection check, which is accomplished in three minutes, and a periodic inspection performed at 500 flight-hour intervals, which can be performed on-wing in one hour, are required. On-condition monitoring coupled with simplified LRU installation and rigging with no required adjustments will allow the T700-GE-700 to achieve a mission readiness far superior to its predecessors.

### On-condition operation:

- requires proven, reliable, durable engine
- utilizes engine status monitors
  - engine history recorder
  - torque reading
  - turbine temperature
  - oil level gauges
  - oil pressure/temperature
  - filter impending bypass indicators
  - fuel pressure
- enhanced by fault isolation features
  - chip detectors
  - borescope ports (7)
  - filter bypass indicator
- no time-scheduled engine maintenance actions.

#### D. MANUFACTURING

The manufacturing stage is as critical as design, management, R&M, etc. Manufacturing can make or break the best of designs. There is also a need to have manufacturing engineers with equal billing during the design phase. This is especially true where manufacturing costs are concerned. There are usually several ways an item can be manufactured but often the design is driven only by the fact that one method can deliver an item early for development with inadequate consideration to production costs. The case studies pointed out activities related to the engine programs that have strong merit. This included pilot production runs, early testing, corrections of problems found through an aggressive failure analysis/corrective action program, continuous review of manufacturing procedures and personnel training, and numerous program reviews.

Failure reporting was the key to ensuring success. But the inspection and test criteria established to provide identification of the failures had to be such that no problems were overlooked. The studies indicate as much effort was expended here as on any other part of the program. Testing had to be tailored and directions explicit. Tolerance flags were established that would call attention to potential problem areas. To this end, the relationship between design and reliability engineers had to be very close.

In-process inspections were also heavy players. Periodic checks and sample sizes must be adequate to provide an absolute minimum of bad components from entering the end product. This meant that explicit details had to be developed and adhered to.

A last element which is implied, but not addressed in strong terms, is employee morale and involvement. A sense of belonging is essential to good quality control and inherent good performance. If the worker is not involved with the program, then the best plans and designs will not provide the system required.

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On-condition maintenance techniques are currently being utilized successfully both in the factory and in the field. Of particular value has been the engine history recorder time-temperature integrator to measure hot-part life used and for comparing the relative severity of field-test engine operation with specification endurance test cycles. The engine chip detector has proven to be an effective means of detecting incipient oil-wetted part failures. Borescope inspection has also proven to be useful and easy to do both in the factory and on the wing. Ground use of the diagnostic connector for control troubleshooting has been effective, even though the currently available test box is only a non-powered resistance checker (Ref. T700 Case Study, p. IIC-56).

The T700 case alludes to a FRACAS type system, but without a formal defined structure. The need during the prototype engine period for a "very early experience base" and recognition of the need for a FRACAS type system so "early development problems could expeditiously be addressed and changes factored into the production engines in manufacture" was clearly evident.

The T700 design engineers and reliability engineers worked closely with production engineers on a daily basis to assure that no problem went unnoticed/uncorrected.

The T700 design review process is presented as a form of failure/correction action review board (Ref. T700 Case Study, p. IID-4).



## E. TEST AND EVALUATION (T&E)

Test and Evaluation is the proof of the pudding. But, like everything else, it must be done correctly. The case studies of the successful engine programs show this in no uncertain terms. Requirements to which the system has been designed must be verified and evaluated through all stages for the acquisition cycle. Planning and preparation require as much care as design and control. Testing of a mechanical system requires that qualification tests be performed to verify design limits, demonstration tests verify design operational requirements, airframe integration tests to verify generic flight and user requirements, R&M growth and maturity tests, and full operational testing in the field. Results from all tests and assessments from field results are the follow-on to the formal tests to find trends and design errors that require corrective action prior to full-level production.

Throughout the testing process, R&M must be reviewed constantly. Growth of R&M in the system must be accounted for and change incorporated in design, assembly procedures or parts requirement addressed to ensure the delivered end product meets the required R&M levels. Growth or maturation tests to specifically address R&M in quantitative terms are required to verify conclusions reached from data analysis. Timing of such tests is vital in obtaining a true picture. Again, well-defined requirements are of great importance. The case studies strongly point to this and stress the importance of addressing the entire R&M area when developing the test and data review criteria.

In concert with the R&M tests, a factor of significance is to be able to fault isolate failures and take corrective action. Such action includes TAAF actions as well as simple mechanical adjustments. The bottom line is that the failure mechanism must be known to ensure a successful fix. Failure reporting and documentation of failures for trend analysis is important

to meet the needs of the R&M staff. Those successful programs performed these tasks well and as a result met and, in many cases, exceeded their required criteria.

#### 1. Integration Testing

Integration testing on the final use platform is another element noted in the case studies as "successful systems." In some instances, multiple platforms are designated as users for a system and testing on each provides a wealth of data pertinent to the program's success. Tailoring of such tests to the schedule and cost is a key planning factor. There is also the need to make certain that accurate failure reporting is maintained.

#### 2. Design Limit Qualification Tests

Testing to design limits addresses a very broad spectrum of requirements. This includes components to environmental (i.e., vibration, temperature, and contaminant ingestion) tests developed in this area and must be well-tailored to provide data that accurately validate that the requirements have been/will be met. In some cases, accelerated tests are required and again planning and well-defined test details must be established. Test severity levels must be adequate to provide reliable data. If the criteria are not specific and broad interpretation of results is allowed, then credibility and success likelihood are placed in jeopardy. Adherence to the above practices was stressed in each of the case studies performed for this study.

### 3. Reliability Growth Testing

The T700 growth program was incorporated into a Maturity Program. The overall program timing planned by the Army provided for competitive test (GCT) of the two different aircraft, each of which was powered by the same configuration T700. The test was begun at about the same time that engine MQT was completed. Under prior program standards, engine qualification would be considered complete at this time and the engine would have been committed to production. At this point, a post-MQT program was initiated with the goal of accumulating additional endurance experience and subjecting the engine to more LCF testing.

The overriding purpose of the Maturity Program was to provide a mature, reliable engine prior to full-rate production. To accomplish this, the following objectives were established:

- Develop high initial mean time between failure-require overhaul (MTBFRO).
- Establish sound field maintenance procedures and intervals.
- Identify unique installation-related failure modes.
- Establish program for smooth transition to production manufacture.

The approach selected was to conduct accelerated, service-abusive tests so that the required production target dates were ensured.

A secondary benefit of the Maturity Program was that it provided a highly valuable period to resolve residual problems uncovered in the field and factory programs and any that might evolve from the aircraft GCT. In addition, a smooth transition to production through producibility and manufacturing technology programs was made possible, as well as the implementation of cost reduction programs prior to production (Ref. T700 Case Study, p. IIE-32).

#### 4. Demonstration Testing

The test program on the T700 did not include a reliability demonstration test with an accept/reject criterion for reliability. All development tests were used to estimate the reliability of the product. The program did include formal maintainability demonstrations.

a. Reliability Demonstration. From the very beginning of the T700 development/qualification test program, every malfunction or discrepancy was documented both in the factory as well as at the various UTTAS and AAH Flight Test Programs. Factory development problems were documented on development problems reports (DPRs) and field problems were documented on DV-7 forms. Thus, every T700 engine test hour, both in the factory and in the field, represented an input for the T700 engine reliability program.

As indicated above, the reliability tracking/analyses were continued as part of the post-MQT Maturity and Life Verification Testing.

Approximately 35,000 engine operating hours were logged by the time the first T700-GE-700 production engine was delivered in March, 1978, thus providing an excellent reliability demonstration base upon which to base the engine's mean time between failures (MTBF).

With the introduction of T700-powered Blackhawks into the field in 1979, a field tracking system was initiated (Ref. T700 Case Study, p. IIE-46).

b. Maintainability Demonstration. As indicated in the T700 case study, a very early maintainability demonstration was funded by the U.S. Army and was accomplished on the ATE (GE12) demonstrator engine in 1971. With the award of the development

contract in March, 1972, the Maintainability Program Plan for the T700 engine was set into action. The following paragraph was extracted from this plan. The total plan describes the three official maintainability demonstrations required by contract:

Maintainability Checks/Demonstrations - The contractor shall conduct the following maintainability checks and demonstrations and shall coordinate the effort with all other interfacing specialty disciplines and the ILS program. The plans for conducting the first engine tear-down and the maintenance evaluation will be submitted in the monthly progress report in accordance with data item DI-R-1741 and addendum dated 19 March, 1971, part, component or subsystem test plan(s).

(Ref. T700Case Study, p. IIE-52).

## 5. Operational Testing

The purpose of Operational Testing is to place the system in a full-up configuration and verify its success in meeting users needs and requirements. Hands-on experience is gained and faults are identified by the user that the designer may not have fully anticipated. Adequate and accurate fault reporting during this phase is essential to providing a true picture of the program's compliance to the requirements and users needs. It is here that the first true evaluations of R&M factors and requirements are seen. The feasibility of the maintenance concept is assessed and attainment of requirements is checked; questions such as accessibility of components, use of captive and foolproof fasteners and connectors, etc., are truly addressed. The results allow the full production effort to begin and start the data collecting for "in-service assessments" to begin.

A helicopter development "first" was pioneered by a joint U.S. Army/GE team by simultaneously developing a new turboshaft engine and four different experimental helicopters. The four aircraft were involved in two major flyoff competitions, UTTAS and AAH. The T700 and UTTAS were developed simultaneously under auspices of the Materiel Development and Readiness Command (DARCOM) UTTAS Program Manager's office, with AAH starting almost 12 months later (See Fig. D-10).

All four types of twin-engined experimental helicopters used identical versions of the YT700-GE-700 turboshaft engine--unprecedented for simultaneous engine/helicopter development (Ref. T700 Case Study, p. IIE-68).

A key factor in successfully integrating a single-engine configuration into four helicopters is a thorough, pre-field-test propulsion system integration effort: factory engine environmental and "fleet leader" testing, repeated Army/GE/AVM design and test reviews, and factory performance and vibrational testing for each installation.

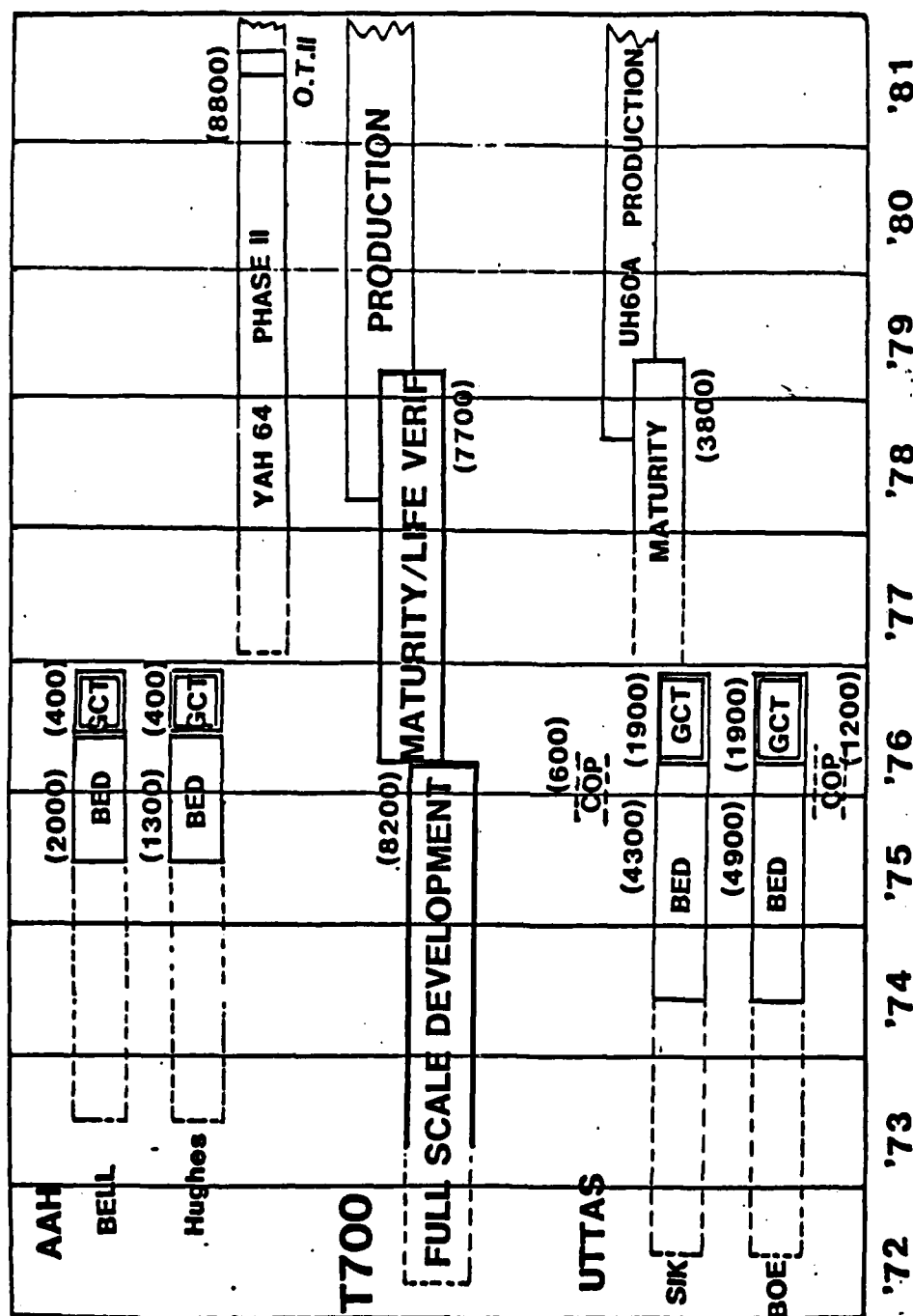


FIGURE D-10. T700 Blackhawk Development Program

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Engine reliability data and installation "lessons learned" from the 18,000 engine test hours accumulated during the UTTAS and AAH Programs represent an invaluable opportunity to examine four different propulsion systems in a concentrated time period and apply the "lessons learned" from actual operational testing into early corrective actions resulting in accelerating the reliability growth of the engine (Ref. T700 Case Study, p. IIE-68).

The Army's UTTAS development philosophy included testing that went far beyond the normal extent of the typical competitive flyoff program. Both Boeing Vertol and Sikorsky were required to demonstrate all production aircraft systems in the working Army environment prior to production contract award. Both AVM's had to produce a brand new aircraft and make it perform as advertised, but they also had to live under the working Army's microscopic evaluation. Naturally, that meant taking prototype aircraft into the mud of Ft. Campbell and meeting predetermined reliability and maintainability goals using the standard Army field team.

The Army was also looking for a full exploration of the UTTAS flight envelope, demonstration of C-141 and C-5A air transportability, and the ability to perform defined UTTAS missions in all types of adverse environmental conditions--icing, heat, cold, night flying, and forward operating sites. Under DoD fly-before-buy concepts, every effort was made to make sure that the U.S. Army knew what they were buying and that the system could successfully live with the field Army (Ref. T700 Case Study, p. IIE-70).

Government Competitive Tests (GCT) started in March 1976 at Ft. Rucker, AL, using two aircraft from each AVM. In May, 1976, aircraft performance and handling quality testing began at Edwards Air Force Base with the third Army-owned aircraft per AVM. During the next seven months, these six aircraft achieved a total of 3800 engine test hours at six different operating test sites: Army User Evaluations were conducted at Ft. Rucker, AL,

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Ft. Campbell, KY, and at a high-altitude Bishop, CA, site. Aircraft icing evaluation was conducted at Ft. Wainwright, Alaska. Each AVUM's GTV was also used for cold/hot environmental ground testing at Eglin Air Force Base, FL.

Primary purpose of GCT testing was to put the production "prototype" UTTAS under a rigid Army User evaluation with the main emphasis on operational realism. Not only were User flight tests flown by randomly selected Army pilots, but all AVUM level (flight line) maintenance was performed by representative Army mechanics, all of whom were monitored by an "Army" of reliability and maintainability data collectors.

Almost 50 percent of total UTTAS experience occurred with Army pilots and mechanics operating in the User's world--a resounding affirmation of the fly-before-buy concept.

During the entire BED Phase and GCT, GE technical representatives documented every engine problem/discrepancy and these data were factored into the Reliability Analyses/Predictions and also provided a 'real world' operational experience base that was unprecedented on other engine development programs. This phase of the program cannot be overemphasized since it provided a direct feedback to the contractor which expedited corrective actions (Ref. T700 Case Study, p. IIE-76).

a. Maturity Program

Following the completion of the Government Competitive Tests (GCTs), the Sikorsky-built YUH-60 was selected for production and designated as the Blackhawk. A follow-on Maturity Flight Test Program contract was awarded to both Sikorsky and General Electric. The three prototype YUH-60's and the GTV were subjected to a limited update program and the YT700 engines were returned to the factory and updated to incorporate several fixes which had been identified during both the Development/Qualification Program and the BED Phase and GCT field programs. These engines were

designated with an 'R' after the serial number to indicate the retrofit.

The Blackhawk Maturity Flight Test program resumed in late 1976 and continued into 1979 with an overlap of the Blackhawk Production Program. During this Maturity Flight Test Program several aircraft qualification tests were completed as well as envelope expansion. GTV running continued to qualify main transmission and drive-train components. During this Maturity Program approximately 3800 engine hours were accumulated and throughout this program GE technical representatives continued to document all engine discrepancies to expand further the Reliability base on the engine. As noted above this direct feedback of operational problems to the contractor was invaluable.

b. AAH Program

An outgrowth of an RFP issued in late 1972, Hughes helicopters and Bell Textron were selected by the Army in mid-1973 to compete in the AAH flyoff competition. Both AVM's had selected the standard T700-GE-700 turboshaft engine (already being developed for UTTAS) as an integral part of their propulsion system. The Army's Phase I Program conformed to the classic flyoff competition format: basic flying quality was to be demonstrated along with an assessment of the technical risk areas, but subsystem development with subsequent integration and aircraft maturity were minimized in order to expedite selection of the winning AAH design and introduction of the production attack helicopter. Unlike the UTTAS full-scale "fly everything before you buy" approach, the AAH competitors did not need to demonstrate all the fire control, night flying, and weapons systems that were to be incorporated eventually into the Phase 2 development and production models. The Army conducted abbreviated user aircraft evaluation. Flight evaluation was conducted by experienced Army pilots, with

Reliability and Maintainability monitoring by Army data collectors.

The AAH Program was originally scheduled to be 16 months shorter than the UTTAS competitive cycle--35 months from initial contract awarded to completion of the GCT Program. Although cost increases and aerospace material shortages in the late 1973, early 1974 time-period contributed to a six-month program slippage, the AAH Phase I Program and GCT were still completed 12 months faster than the UTTAS Program. Still, the AAH flight-test program averaged 20 percent more YT700 engine operating hours/aircraft/month than the UTTAS Army program [63 vs. 53 hours] (Ref. T700 Case Study, p. IIE-80).

Phase I testing (equivalent to the UTTAS BED Phase) started with GTV operation in June 1975. By the end of ground testing in May 1976, the two competitors had completed 1300 hours of XT and YT700 engine operation. Unlike UTTAS, which utilized GTV testing to demonstrate long-term "fleet leader" reliability, AAH GTV testing was limited to 50 hours of preflight aircraft qualification and subsequent follow-on qualification (up to 150 hours) of the propulsion system and drive train. AAH flight testing was initiated in September 1975 and, by the conclusion of Phase I in May, 1976, both Hughes and Bell had accumulated 1700 YT700 engine operating hours with the two flyable aircraft operated by each company. Since UTTAS testing had already been in progress for 12 months, many initial engine operating problems and troubleshooting procedures had already been resolved, thus significantly speeding engine/airframe integration during the initial portion of AAH flight test. The AAH flight test program was supported by 28 YT engines evenly distributed between the two test sites and four SRD engines kept at GE's Lynn, MA facility for rapid verification and qualification of field-related problems.

The primary goal of Phase I flight testing was a preliminary exploration of the aircraft performance envelope and validation of basic handling qualities. In addition, some limited propulsion system flight surveys were conducted by joint GE/AVM teams and the basic 2.75-inch rocket and 30-mm gun systems were demonstrated. All ground and flight testing was conducted at each AVM's flight test facility: Hughes helicopters at Palomar, CA and Bell Helicopter at Arlington, TX (Ref. T700 Case Study, p. IIE-82).

The Phase 2 program was a 56-month full-scale engineering development wherein the two Hughes helicopters from Phase 1 were modified to the latest configuration. Three more helicopters were built, and development of the HELLFIRE missile, 30-mm cannon, and 27.5-mm rocket subsystems completed. Also competitively developed were the target acquisition-designation sight and pilot's night-vision sensor. The subsystem and all mission equipment have been integrated and thoroughly tested. The Army Operational Test II was completed with the APACHE accumulating over 400 flight hours during June-August 1981. A total of over 4,000 test hours were flown on the YAH-64 prototypes. The residual AAH weapons system testing and other related essential activities were also completed.

Long-lead-time contracts for production of the APACHE were awarded in February 1981. The initial production contract was awarded 15 April 1983.

During the entire AAH Flight Test Program, GE technical representatives have documented all engine discrepancies and these data have been processed through the Lynn Product Data Center and T700 Reliability Operation for inclusion in the Reliability Analyses/Predictions.

## 6. In-Service R&M Assessment

The in-service assessments are important to the acquisition program and R&M growth because of the identification of problem areas and trends not seen earlier. These assessments also provide the supply and maintenance information needed to refine the logistics support requirements and identify critical areas where actions are required. It is important that in-service assessments be started as early as possible in the program. In the T700 program they were started prior to the Government Competitive Tests. By now the T700 has completed one-quarter of a million operating hours and is receiving exceptionally high marks.

Using a 90-day rolling average the shop visit rate for all causes during 1982 hovered around 0.5 which is the maturity goal for the engine. Engine-caused removals account for about half of the rate, or approximately 0.25, which is comparable to large commercial engines. That converts to an engine-caused MTBR of approximately 4,000 hours--quite a record when compared to 1960's engine history. As a comparison, the T700 shop visit rates for various causes generally are running from zero to 50 percent that of the earlier powerplants (see Figure D-11). It may also be noted that earlier engines had a TBO while the T700 does not because it has been "on-condition" from day one.

A maturity goal of 1.6 removals per 1,000 engine flight hours for all causes, for LRUs, was also established. In the beginning of 1982, LRU removals were running approximately 2.0. That rate has dropped sharply and is now close to the maturity goal. Incorrect LRU removals have been in the range of 30 to 50 percent; particularly, the HMU and ECU. It has been found that the ease of removal and replacement can lead to "gang" troubleshooting rather than a logical fault-free analysis laid out for the mechanic in the engine field technical manual. Through improved troubleshooting reviews by GE's product support organization and assistance by on-site technical representatives, the

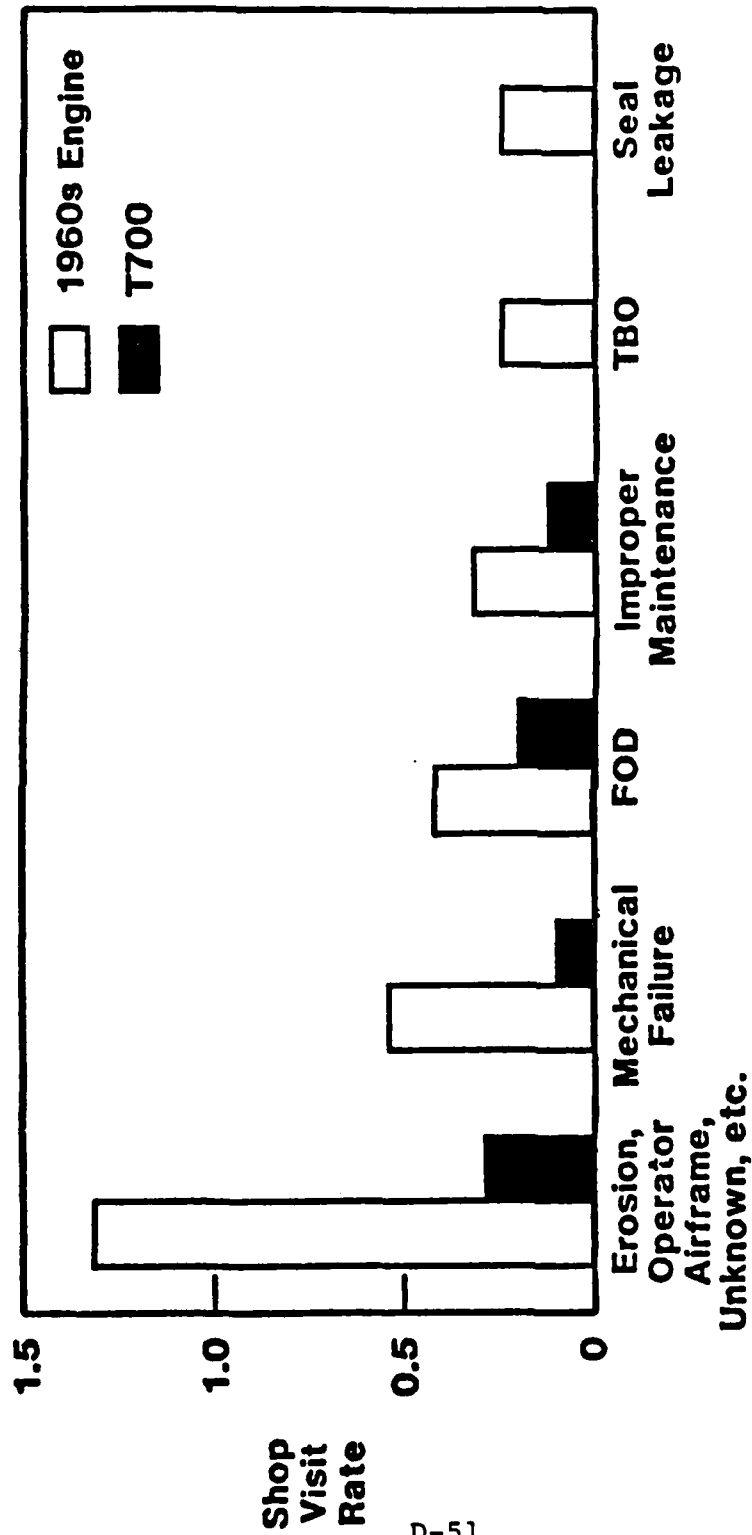


FIGURE D-11. Shop Visit Rate Comparison

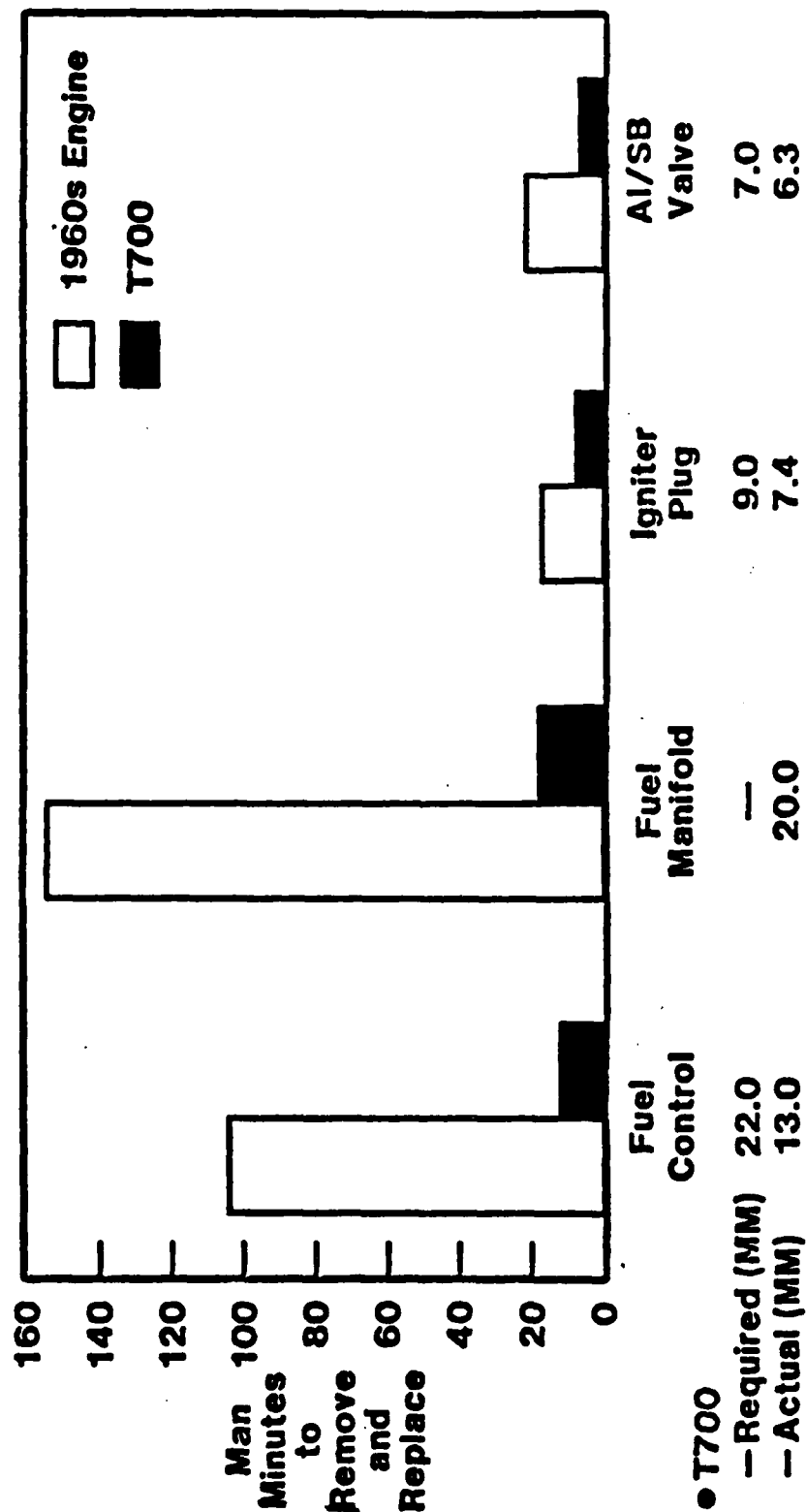


FIGURE D-12. Flight Line Maintainability Comparison

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incorrect removal rate is decreasing. In addition, GE has developed a system analyzer, now being evaluated by the Army, which is designed to isolate those sometimes difficult electrical circuit faults. The Army is currently reviewing the very successful field history of two prototypes to determine if they will award a limited production contract.

Flight line maintenance represents 60 percent of the maintenance actions. A comparison between the T700 and 1960's engines of the man-minutes required to remove and replace four elements is shown in Fig. D-12.

The maintainability requirements of the T700 are exhibited most dramatically, perhaps, by the fact that approximately only one man-year of corrective maintenance man-hours has been required on the T700 during its first quarter million hours of service. This includes all T700 engines at all Blackhawk operating sites. There have even been complaints from maintenance officers about maintenance personnel losing proficiency because there is not enough maintenance activity on the T700 to keep them sharp. This is perhaps true in spite of the fact that 2 to 3 fewer engine mechanics have been assigned to Blackhawk units than to "Huey" companies (Ref. T700 Case Study, p. IIE-108).

Dedicated on-site Field Monitors collected and edited R&M data on the UH-60A Blackhawk program as part of the Sample Data Collection (SDC) program. Additional Blackhawk R&M data were collected from the three-year T700 Reliability Improvement Program and from CRIM (Comprehensive Record for Intensive Management) records which were completed each time the user removed one of the components selected for intensive management."

#### F. OBSERVATIONS

In summary, the T700 at 250,000 hours has established an outstanding record compared to mature prior generation engines.

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One result of the improved R&M characteristics has been reduction in engine spares to 15 percent rather than 50 percent, a saving of \$400 million. Major conclusions to be drawn from the development experience with this engine are:

- The Army's careful preparation of the reliability and maintainability requirements, and its insistence that they be met, are already producing a pay-off in low shop-visit rates and line replaceable unit removal rates. GE and the Army now can concentrate more on improvements to the engine rather than "fix-it" programs (Ref. T700 Case Study, p IIE-16)
- The 6.3A demonstrator engine program extended over an 11-year period without funding disruptions which allowed an orderly development without fluctuations in personnel. Approximately \$200 million in RDT&E funds were provided for this effort.
- The early-on warranty allowed the contractor to have configuration control and total logistics latitude to introduce corrective actions quickly before the fleet had a chance to grow, which would make corrective action more costly and complex to implement (Ref. T700 Case Study, p. IIE-116).

As a result the T700 has already developed a reputation for being a low cost of ownership engine that is highly reliable.

In retrospect, it is also possible to see ways in which the development of engines could be done better. One major recommendation that originated with the contractor is that Accelerated Mission Testing (AMT) be started much earlier in the program. The reasons for this recommendation are as follows:

Looking at the T700 test programs in chronological order,

it is easy to see the learning process develop as the factory test program becomes more and more oriented toward Accelerated Mission Testing (AMT) type of tests. The T700 Qualification Program included two 150-hour MQT tests as well as two 1,750-cycle LCF tests to gain confidence in, and to demonstrate the integrity of, components directly affected by LCF damage. More AMT-type testing could have accomplished the same results using fewer engines and less time. The potential cost savings are evident.

To provide additional confidence in the long-term integrity of engine components, 1,000-hour MQT endurance tests were initiated in 1976. The first real Accelerated Mission Testing was initiated with the 1,500-hour Blackhawk ASMET test. It was not until later, in 1978, however, under the Component Improvement Program (CIP), that substantial AMT testing commenced in which engine parts were exercised in ELCF, EFTC and ETAMP in proportions representative of anticipated field usage.

For many years now, the MQT-type test cycle has served as the standard used to qualify alternate sources. It is suggested here that the time has come for a new standard to be established--the AMT test cycle. This focus on AMT testing should be integrated into the Full-Scale Engineering Development Program at the outset of FSD. The objective is to achieve early maturity for the engine design during the FSD program and to eliminate or minimize the need for a follow-on Maturity Program Phase. The T700 development program incorporated the Maturity Program concept conceived by the U.S. Army to identify and fix component deficiencies which may occur in engines that are not fully mature before entering production. This program has significantly contributed to the T700's successful field experience.

It is recommended that future Full-Scale Engineering Development Programs focus on AMT testing from the outset of the program. AMT testing accomplishes much more in establishing parts life integrity and exercises all parts in production to

their intended field usage. AMT testing, as part of an overall engine life management program coupled with a fleet leader program and sufficient engine usage monitors will lead to even higher standards of engine reliability and lower life-cycle costs than has been achieved in earlier programs (Ref. T700 Case Study, p. IIA-58).

In addition, based on the T700 experience, some corrective actions have been identified by the Army for current developments as follows:

- Increase test hours in the 6.3A program to allow for limited LCF and abusive testing. This action has already been initiated on the 800 HP ATDE and the 5000 HP MTDE programs.
- Validate Inlet Particle Separator (IPS) performance as part of 6.3A program. This has been incorporated into the ATDE and MTDE program.
- Establish common power turbine speed for competitive 6.3A demonstrator programs. This has been incorporated into the ATDE and MTDE.
- Include producibility and design to unit production cost from the outset. These items have been incorporated into the ATDE and MTDE.
- Refine the balance between reliability/maintainability. The current MTDE reflects a better balance (e.g., reduced number of modules for increased reliability).
- Eliminate the time gap between advanced development and engineering development programs. This requires a management decision by DoD and DA to commit to development of generic engines prior to the firm aircraft requirement.

There are also specific problems which continue to appear as more extensive field experience is accrued. A review of the conditions of field returned T700 engines by the AVRADCOM Directorate of Product Assurance led to the following observations:

"Our observations were that most of the returns were the result of externally-induced failures as a result of the aircraft power extraction shaft failures. The areas of high-cost repairs were FOD damage to the compressor and diffuser section. The second observation was on engines returned for low power had eroded and contaminated (dirty) compressor sections. GE was running engines as received to obtain baseline data performance deterioration. Engines with low power have the potential for extended service if adequate compressor cleaning is accomplished, as demonstrated by the GE test and subsequent cleaning. Reducing the compressor efficiency results in the loss of efficient power, which increases both direct and indirect O&S costs. A specific recommendation is made for all future propulsion systems that a water wash system with tanks be made a component of any modern technology engine. The purpose is to realistically facilitate a method to maintain compressor efficiency; a water wash system must be part of the pilot's operating procedure. Specifying it as a maintenance function (i.e., every 100 hours or as required), is labor intensive and not complied with, per our observation. The third observation is a general RAM improvement program of gas turbines. Recommend that a Product Assurance life-cycle RAM plan be adopted to ensure that the contractor and Government have within their RAM management concept a commitment to provide life-cycle feedback subsequent to production and fielding. The prime manufacturer's RAM concepts should include a Government commitment to allow the contractor to have a RAM evaluation program via a life-cycle minimum repair allocation of engines. The purpose is to ensure that feedback is maintained to evaluate production and overhaul changes introduced during the life cycle

that can be correlated back to the original production margins and performance factors. The current practice of internal military overhauls precludes a life-cycle product assurance feedback system to the prime and may allow him to repeat design and manufacturing processes which are detrimental to RAM and life-cycle costs because of the lack of a quantitative feedback system under his control.

It is the general observation that the Army has made a significant RAM contribution in supporting the T700 as a highly reliable propulsion system and should continue the same type of approach on a new generation propulsion system; and, when production requirements are adequate two competitive contractors should be maintained in order for the Government to obtain the benefits of competition."

Extensive field experience has also surfaced some potential design improvements as follows:

- Integral Inlet Particle Separator. In spite of the 85 percent efficiency of this device in separating sand and dust, it remains inadequate to the engine requirements. Larger particles peening the Stage 1 blades are a significant factor in limiting on-wing life due to performance loss. In moderate environments (i.e., Ft. Campbell/Ft. Bragg) engine performance can degrade to the reject limit in 1000 to 1400 hours of operation.
- Axi-Centrifugal Compressor. The "blisk" concept appears to have been sound, with a single, notable exception. The first stage "blisk" incurs a large amount of FOD, and degrades rapidly due to sand peening of the blade leading edges. In retrospect, a design allowing for field replaceable Stage 1 blades would have offered superior maintainability/reliability.

- Anti-Ice Start Bleed Valve. This dual function valve is now in its second redesign. It appears that in an effort to reduce the number of systems/parts, an overly complex and very sensitive device resulted. A large number of malfunctions of this device have resulted in mission restriction in some theaters and excessive downtime. In retrospect, separate anti-ice and start/acceleration bleed systems would have been desirable.
- Electronic Control Unit. This unit remains very costly, and labor intensive to manufacture, repair or modify. Electronics state-of-the-art has advanced far beyond this design, leaving it obsolescent. Due to cost and support limitations, intensive logistics management is required to provide adequate fleet support.

APPENDIX E

DEVELOPMENT OF DIAGNOSTICS

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## APPENDIX E

### DEVELOPMENT OF DIAGNOSTICS

The development of diagnostics is an immature discipline when compared to reliability. The terms for contractual and operational reliability are not the same, but they are predictable and can be related. In diagnostics, there is no clear definition of requirements which can be used for contracting, is understandable to a designer, and is closely related to a field measure. For reliability, there are well-understood design tools for analysis of the stresses which cause failures as well as predicting failure rates for components, subsystems and systems. Design tools for diagnostics are much less structured and practiced.

In reliability testing, there are proven techniques for simulating the operational stresses an equipment will undergo, weeding out the causes of unreliability and verifying the potential system reliability. Diagnostics testing techniques are much less mature. Though fault insertions are performed, they are not good predictors of field performance. They will indicate whether there are problems, but success in such a demonstration is no guarantee of a good design. Thus, demonstration by fault insertions are necessary, but not sufficient.

During early operational introduction, the assessment of reliability is much more straightforward than diagnostics. There are some problems with using field data to assess reliability during full-scale field operations. However, the problems with the data systems are understood well enough that field reliability data are useful for some management purposes (trending if not in an absolute sense). The data system is almost useless for diagnostics. It does not reflect the method of detection/isolation,

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human intervention in the decision process, or troubleshooting time factors. This lack of knowledge in the diagnostics arena (contracting, requirements, design, testing, employment) presents a significant challenge to the military and industry communities in the improvement of current systems and the acquisition of future weapon systems. Fundamental work is required in all these facets of weapon program development to produce acceptable diagnostic capabilities in the field.

#### A. DIAGNOSTICS TERMINOLOGY

A fundamental indication of a problem in diagnostics is the many inconsistent and overlapping terms and definitions used to describe and measure diagnostics capability. One of the recommendations of the report is to generate and standardize a comprehensive set of diagnostics terms. This section does not do that; it is simply a discussion of the terms in the report so that the reader can relate his own experience with diagnostics terms to those presented here.

Describing Capability: From the perspective of the prime system user, the basic functions of a built-in-test capability can be categorized into four groups: system health monitoring, expanded/initiated fault detection, maintenance health monitoring/fault duplication/correction verification, and maintenance fault isolation (on-line or off-line). The terminology used to describe these functions may not distinguish between them and the terms may be used differently from program to program. The important point is that, without standard terms, a lengthy communication/definition process is required for all parties (materiel developer, contractor, user, and tester) to understand the objectives and capabilities of diagnostics in a given program.

In general, most automated diagnostic systems have two basic capabilities: health monitoring/fault detection and fault

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isolation. The first capability usually runs whenever the system is turned on, it monitors functions without interrupting system operation, and it requires no initiation from the operator. In some programs (e.g., F-16), this is called self-test or continuous BIT which emphasizes the non-interruptive characteristic from the crew's perspective. In other programs (F/A-18), this capability is called periodic BIT which emphasizes that the monitoring functions are performed at specific times during system operation. Most systems also incorporate a capability for the operator to initiate further test activity in order to determine the extent of the problem. This usually requires some interruption of system operation and is called BIT in the F-16, and initiated BIT in the F-15 and F/A-18.

Both the self-test and the interruptive or initiated capability can also be used as the maintenance fault detection tool to detect malfunctions, confirm reported malfunctions, and verify actions taken to correct malfunctions. The initiated BIT may also be designed as the maintenance-fault-isolation tool. However, if off-line diagnostic routines are loaded to perform this task, the capability is sometimes given the name, fault isolation test (FIT).

Measurement Terms: In the case studies and throughout the diagnostic literature, there are numerous approaches for improved measurement of diagnostics performance. The focus here is to use relatively common operational terms. Though the terms are common, there are significant differences between the Services and various programs. The term "false alarm" is an example of the definition problem.

The Navy typically uses the term false alarm to refer to those BIT indications to the aircrew which results in an organizational level action of A-799 (no defect), plus those maintenance actions which result in an organization (O) level weapons replaceable assembly (WRA) removal followed by an A-799

in the intermediate (I) level shop. It is, thus, the ratio of O&I level A-799s to the total BIT detected maintenance actions. It is a BIT maintenance effectiveness number analogous to the Air Force terms O level CND and I level bench-check serviceable (BCS) or retest OK (RTOK). The false-alarm denominator is total BIT detected maintenance actions.

The Air Force's typical use of the term, false-alarm, refers to those BIT indications to the aircrew which are unaccompanied by system degradation, not debriefed as problems, and they do not become maintenance actions. It is thus a measure of the quality of BIT data presented to the aircrew. The false-alarm denominator is the total BIT fault indications.

In a contractual sense, false-alarm rate can be used in either of the ways indicated above. However, it has also been interpreted in a third sense; that is, as the ratio of incorrect BIT indications to total BIT inquiries. The denominator in this case is the total number of times BIT measurements are made whether they result in an indication of a fault or not.

Because of the significant differences in the definitions of false alarm, it is important to understand which is being used in a specific application. In the case of the F/A-18 (APG-65 radar), the Navy operational testing threshold for false alarm was 20 percent, which is a very stringent requirement. Early operational measurement of the radar false-alarm rate ranged from 69.5 to 79.2 percent. The contractual requirement was for a false-alarm rate of  $\leq 2$  percent.

The Air Force definition of false alarm was not levied as a requirement on the APG-66 radar, nor was it measured during service test and field operation due to a lack of recording capability to capture all the in-flight BIT indications. On two other complex avionics systems (E-3A Surveillance Radar and B-52 OAS) which had a recording capability, the false-alarm rate was on the order of 70 to 80 percent.

The third definition is not applicable to the three radar examples in this case study. However, an unrelated example should help to understand what the order of magnitude for this definition should be. In this program, the required false-alarm rate is 2 percent. The denominator is the number of times BIT measures a parameter. This particular BIT system measures 12,000 parameters during pre-flight and every 30 minutes during flight. In a 4.5 hour flight, there are 12,000 X 10 or 120,000 measurements made. A 2 percent FA rate would mean that there could be as many as 2,400 false indications. Operationally, this does not sound like a constraint at all when one considers the aircrew having to deal with this much false information and distinguish it from true fault indications. Instead of 2 percent, the requirement should more properly be .002 percent or .0002 percent.

In summary, false alarms by any definition have an operational impact. It is important to specify exactly what definition of false alarm is being used on a specific program. Depending on the definition, a 20 percent FA rate can be very stringent and a 2 percent FA rate can be very loose.

In this report, false alarm will be used to refer to indications to the crew which do not become maintenance actions, except where it specifically applies to the F/A-18.

Cannot duplicate (CND) will be used to refer to those organizational level maintenance actions in which no repair action is taken because the reported problem could not be duplicated. There are instances where a problem cannot be duplicated but a unit is removed because it is suspected to be a possible cause of the problem. Though one could make a case that this should be called a CND, it is not reported as such in the data system and will not be considered a CND in this discussion.

Bench-checked serviceable (BCS) will refer to those units removed for cause which subsequently check serviceable at the intermediate level of maintenance (Navy: A-799 at level 2).

Retest OK (RTOK) is sometimes used to describe what is defined above as BCS. However, in this discussion, it will apply to a unit which checks serviceable when sent to the depot level for repair.

#### B. CURRENT PRACTICE AND SUCCESS

For the past decade the typical diagnostics requirements for complex avionics have taken the form of 90-98 percent fault detection, 90-98 percent fault isolation, and 1 to 2 percent false alarms, though the latter is not always specified. Design techniques and contractual demonstrations have evolved to meet these requirements. However, though they have been achieved in a contractual sense, they typically are not met during early operational testing. Figure E-1 shows the requirement and contractual demonstration

	REQUIREMENT	CONTRACTUAL VERIFICATION	INITIAL FIELD TEST
F-15 APG-63	% Detect	95	Low
	% Isolate	95	Low
	% False Alarm	2	High
F-16 APG-66	% Detect	94	24-40
	% Isolate	95	73-85
	% False Alarm	-	34-60
F-18 APG-65	% Detect	90 (98)*	47
	% Isolate	90 (99)*	73
	% False Alarm	2	72

\* Requirement for Periodic BIT (Initiated BIT)

FIGURE E-1. Radar Diagnostics: Success or Failure

results of three airborne radars. Though the demonstration requirement was substantially achieved in all three cases, field testing resulted in a significant shortfall. These cases are not unique. Future programs should be built on understanding how to define, specify, design, demonstrate and mature a diagnostics capability which is effective during operational employment by Service.

## 1. Requirements

The current built-in-test requirement development process has been the concern of the military as well as contractors. To properly develop requirements so that the problems experienced with BIT (namely insufficient detection, improper fault isolation and excessive false alarms) can be eliminated from designs requires guidance in identifying BIT design drivers and formulating design decisions to preclude as many of the identified problems and concerns as possible.

The problems were addressed in the OSD, February 1981 BIT Requirements Workshop (reported in IDA Paper P-1600, August 1981). This government/industry workshop was sponsored by the Office of the Assistant Secretary of Defense (MRA&L) to assess progress and problems in specifying, testing and evaluating BIT in complex electronics equipment. The following is an overview of the problems and positions expressed in the report which have application to the development of design requirements.

- BIT-equipped electronic subsystems being introduced into the field today are universally not meeting the diagnostic specifications which are generally in the range of 90 to 95 percent probability of automatic (or semi-automatic) fault detection and isolation.
- 20 to 40 percent of items replaced are found to have no failure when tested at the Intermediate or Depot level.
- BIT, in general, is not designed to detect all failures. Consequently, manual troubleshooting is required to augment automatic BIT capability.

- BIT mechanization has not yet advanced to the point where highly skilled technicians are no longer necessary.
- BIT design during system development is not as visible to program management as is electrical and mechanical design.
- BIT contractual specification requirements are open to a wide range of interpretations.
- Early assessment of field operational performance is very difficult because of incomplete software and interactions between operational and maintenance personnel, test equipment and technical manuals.
- Adequate test time (or test articles) generally has not been set aside to develop BIT in complex systems.
- Contractual BIT laboratory demonstration tests (MIL-STD-471) do not provide reliable predictions of BIT performance in the field.
- About two years of field operations with dedicated field personnel and closed-loop data systems have been found necessary to mature BIT in complex systems.

The body of the IDA report presents papers and panel discussions concerning these topics. Its primary purpose was to document the lessons learned and associated recommendations to improve the manner in which BIT is specified, and its design progress monitored and evaluated, both analytically and in tests and demonstrations. The three basic issues of fault detection/isolation, false alarms, and design growth can be identified as underlying all the concerns expressed in the paper.

The fact that fault detection/isolation has been classically equated to probabilities in terms of failure rates of components, components count or failure rates of functions, and the fact that the term confidence in fault detection/isolation can be

interpreted either as a statistical boundary or a limit on false results, illustrates that BIT requirements are also open to interpretation.

False Detection/Isolation: Failure to detect faults of which either the operator or maintenance crew become aware results in mistrust of the BIT and heavier reliance on squawks. Squawks are not always related to failures; they may be in response to normal, but unexpected performance stemming from inexperience, inadequate training/technical orders, or anomalous events that occur during otherwise normal operation. The result is increased maintenance actions, spares depletion and decreased operational availability. Erroneous fault isolation or large ambiguity groups also lead to spares depletion, excess maintenance, the need for higher skills and mistrust of the BIT results. Figure E-2 is an extract from the IDA report outlining past Air Force history of BIT requirements versus results of design analyses. The analyses were based on either field data or study reports, and they draw attention to a generally large disparity between specified and attained values. Many of the equipments were thought to have met the requirements as interpreted by the contractor. The Air Force Operational Test and Evaluation Center focused on this disparity in three operational tests: The E-3A, F-16, and EF-111A. The resulting study identified the problems as basic to the prevailing diagnostic theory. As shown in Fig. E-3, 90 percent fault detection can be attained by checking units 1 through 5 only, since each individually contributes 18 percent to the total failure rate. Similarly, only units 1 through 4 need be isolated to meet an 80 percent isolation capability. The specifications have been met, but:

- Units 6 through 10 may be more mission critical than 1 through 5 and the relative distribution of failure rates may differ from the prediction.
- Fault detection for units 6 through 10 and fault isolation for units 5 through 10, must be performed



NOMENCLATURE	TYPE SUBSYSTEM	% FAULT DETECTION		% FAULT ISOLATION (LRU)		% FALSE ALARMS	
		SPEC	STUDY	SPEC	STUDY	SPEC	STUDY
AN/ARN-118	TACAN	85 (A)	48	M/A	--	N.S.	0
<input checked="" type="checkbox"/> AN/APX-101	IFF TRANSPONDER	90	100 (B)	90	78	N.S.	33
AN/APN-185	DOPPLER	95	71 (C)	95	N/A	N.S.	14
AN/APN-190	DOPPLER	95	61 (C)	N/A	--	N.S.	10
<input checked="" type="checkbox"/> AN/AJK-6	COMPUTER	(D)	91	83	77	N.S.	38
* AGM-69A	SRAM AVIONICS	95	97	M/A	--	2	.1
AN/APG-63	RADAR	95	55	N.S.	30	N.S.	29
AN/ASN-109	INERTIAL NAV	95	56 (E)	95	UNK	N.S.	44 (E)
MADAR (C-5A)	INTEGRATED TEST	N.S. (F)	11	N.S. (F)	UNK	N.S. (F)	89
* CITS (B-1)	INTEGRATED TEST	95	96	75	85 (G)	3 (H)	4
AN/APQ-114	RADAR	UNK	20	N/A	--	UNK	12
AN/ARC-164	RADIO	N/A	--	N/A	--	N/A	--
(A) COLLINS DESIGN GOAL		(E) MAY NOT BE TOTALLY BIT RESULT					
(B) NO INDICATION OF NON-BIT DET.		(F) SPEC REQUIRED 80% AVAILABILITY					
(C) BIT DETECTED AND/OR CONFIRMED		(G) 97% to 3 LRU's					
(D) INCLUDED W/ISOLATION REQUIREMENT		(H) DEVELOPMENT SPEC ONLY					
*MET SPECS	<input checked="" type="checkbox"/> MARGINAL	N.S. = NOT SPECIFIED					

FIGURE E-2. BIT/SIT Improvement Project - Phase I Results

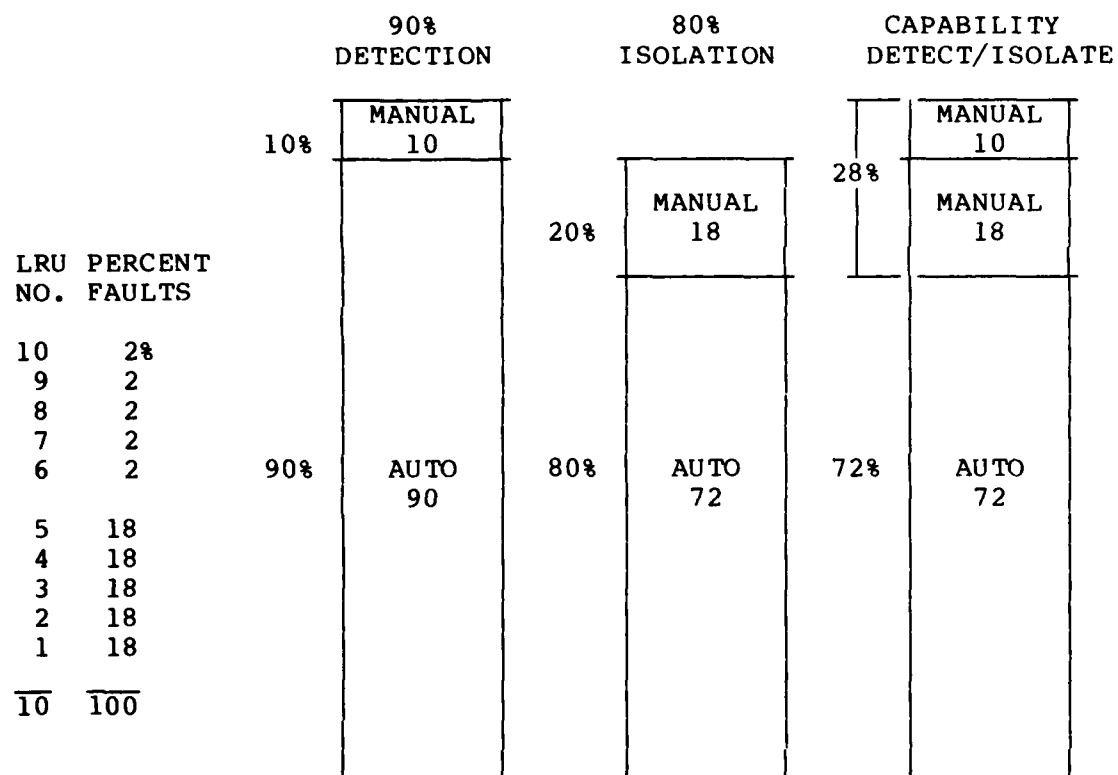


FIGURE E-3. Theory for Designing 90/80% FD/FI Capability

manually, probably based on operator squawks or comprehensive ground tests.

- The BIT design could have left the most difficult testing and fault isolation to be done manually, which is contrary to the objectives of automatic self-testing.
- Wiring and connectors have not been addressed.
- Undesirable indications (which lead to false alarms, cannot duplicate and retest ok conditions) have not been designed out.

Though there was no general consensus as to the exact process of establishing diagnostic requirements in terms of performance levels, it was agreed and recommended that diagnostics must result in meeting operational constraints, and that these should be stated in terms of:

- Identification of safety and mission critical functions including maintenance turnaround time.
- False-alarm rate.
- Constraints on the use test equipment.
- Programmed manpower and skill levels.

False Alarm: False alarms are one of the most serious problems encountered with BIT. They cause false mission aborts, inflight indications where organizational level maintenance testing cannot duplicate the problem (CND), or false removals which retest ok (RTOK) at higher maintenance levels. This results in excessive shoploading and flightline maintenance, which in turn decreases operational availability and increases support costs. In the long run, false alarms result in the operator ignoring BIT indications, which can lead to mission safety problems and excessive LRU swapping which in turn leads to maintenance-induced failures.

The Air Force has expended substantial effort and resources to determine how to eliminate false alarms from BIT systems. Of

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particular note is an RADC (RADC Report TR-81-220) study titled, "Analysis of Built-In-Test False Alarm Conditions". An excerpt from the statement of work is as follows:

"The negative impact of false alarms on maintenance policies and support costs has been documented on a wide range of systems. The extent of these false alarms contributes to the expenditure of excessive maintenance resources such as manpower, support equipment, and logistic supplies. BIT systems that experience high levels of false alarms may be rendered ineffective due to the lack of confidence in the integrity of the failure diagnostic information. False alarms can seriously degrade the mission effectiveness of systems that incorporate BIT to perform system monitoring functions. Erroneous indications of a system's capability may result in an unnecessary mission abort depending on the criticality of the system under test."

"The basis of false alarm conditions rests in unanticipated design deficiencies. Providing designers with guidelines to anticipate and remedy these deficiencies will result in a BIT end product with high level of operator confidence in the validity of the test results. Prediction factors will provide insight concerning and allow for the structuring of maintenance policies to minimize the impact of false alarm conditions."

The study clearly recognizes the impact of anomalous system events and intermittent faults on BIT false alarm rates. There are four possible causes of a BIT fault indication:

1. A valid fault
2. An intermittent
3. A momentary anomaly
4. A false alarm.

Historically, because of a lack of data, the last three have all been categorized as erroneous indications or false alarms.

Complex military systems have a tendency to exhibit momentary anomalies unrelated to the presence of a fault. Most system anomalies do not indicate failure events causing loss of capability or requiring maintenance action.

To quote from the RADC study:

"BIT must be designed to identify and accept 'normal' anomalies without generating a failure indication (false alarm)."

It is very difficult to differentiate between the symptoms of false alarms and those of intermittent faults. Both are inherently transient in nature and extremely difficult (but not impossible) to isolate. The solution to the false-alarm problem should not be allowed to mask the problem of detecting and isolating intermittent faults, and the specified requirements must ensure that it is clear that thresholds of detection cannot be lowered to mask the problem.

The selection of fault detection logic and the associated thresholds must receive a great deal of attention during the design phase, but the actual fault detection threshold settings to be used after operational deployment must be matched to real-world performance, and cannot be firmly developed until flight tests and possibly early deployment. Therefore, requirements must also address and permit BIT growth during the operational phase of a program.

The RADC study recognized that past specifications for BIT performance have been poorly defined at best, and have ignored the problems of anomalies and intermittent faults which emphasizes the care needed in developing contractual requirements.

It is clear from the studies referenced above and this case study activity, that the traditional methods of simply specifying automated detection and isolation rates provide an inadequate foundation on which to design effective operational diagnostics.

## 2. Design

Current diagnostics design practices were built on the existing (or evolving) practices of the reliability, maintainability and logistics disciplines. Identification of the failure modes to be detected was based upon the existing reliability analyses, i.e., the reliability prediction and the failure mode and effects analysis.

These reliability techniques originally addressed only hard or catastrophic failure modes. Today's complex electronics also exhibit many subtle forms of out-of-tolerance performance that are transient and result from timing incompatibilities, unforeseen processing and environments, or operational and diagnostic software problems. The result is that diagnostic analyses based upon less than comprehensive FMEAs produce incomplete estimates of the design's diagnostic capability.

More modern approaches have been evolving and do have the potential to improve diagnostic design. These include management emphasis on diagnostics, architectural schemes which facilitate fault detection and isolation, earlier and more effective logistics support analysis to influence design trades, and emerging techniques for testability analysis. As an example, in the FIREFINDER Program, BIT design was accomplished concurrently with the radar system design. Test point selection was made in system layout. Computer simulation of the signal processor was made to establish optimum implementation of BIT.

Advancing technology in multiplex busing, microprocessors and distributed processing permitted architectures where individual subsystems could be self-contained with respect to fault detection and isolation. Improved partitioning of functions, self-contained BIT integration in subsystem design, and simple subsystem interfaces greatly facilitated fault isolation.

Logistics support analysis, closely linked to the system engineering process, served to focus designers on the operational

support implications of design trades. On the F/A-18, subsystem design engineers were responsible, not only for the performance characteristics, but for R&M as well.

Testability analysis techniques, though immature, have had some impact on achieving diagnostic capability. These techniques aid in the optimum placement of test points, assessing the degree of physical/functional/electrical partitioning achieved in a design, allocating hardware and software to perform BIT, setting test tolerances to balance between failure detection and false alarms, and providing a disciplined structure for achieving vertical testability.

The overall result of these evolving design approaches has been a significant improvement in diagnostic capability over previous weapon systems, such as the F-4, F-111, and the initial F-15. Though false-alarm, CND and RTOK problems have not been totally overcome in current programs, complex electronic systems, such as the F-16 and F/A-18, would be virtually impossible to maintain without the improved design approaches.

In current complex systems, software development (particularly for diagnostics) has become a difficult problem. A hypothetical example illustrates why. At the front end of the design activity, detailed requirements tend to be unfixed, which forces the hard tasks to get relegated to software to be resolved later in design where they can presumably be resolved with little hardware impact. The first design priority is designing the hardware to perform, and the development of diagnostics software lags performance implementation. The software requirements baseline may not even be fully defined by the time testing starts. The testing of diagnostic software, if it is done at all, normally has less emphasis than mission-critical software. The maintainability demonstration employs the diagnostic software, but in a highly controlled environment where known hard failures (not necessarily the causes of false alarms) are inserted. When operational testing starts, the

software is immature, but in addition, the use patterns and environment change significantly from those of the demonstration. At this point unanticipated faults, previously untested software paths, and unexpected occurrences result in undetected failures and false alarms. With proper planning, this experience can be used to adjust thresholds, voting schemes, and alarm decision algorithms. What is needed then is software performance data, software engineering expertise and a rigorous system for tracking and updating software configuration.

Better software design and management techniques would be useful in maturing the software earlier.

### 3. Development and Demonstration Test

Diagnostic testing has included development tests and verification or demonstration tests. Development testing has been performed primarily using either fault insertion exercises or using other tests as targets of opportunity.

Fault insertion exercises were used for BIT development on the F-16 in general and the APG-66 radar in particular. Since system requirements forced the BIT to be self-contained within subsystems, effective subsystem BIT testing was possible. Prior to formal demonstration, the radar contractor inserted over 1450 faults and used the results to improve detection and isolation capabilities. The activity paid off in the formal demonstration where 94 percent fault detection and 98 percent fault isolation were demonstrated for 150 inserted faults.

Besides fault insertion development exercises, contractors have effectively used other activities as targets of opportunity to identify BIT problems. Though not always efficient, these tests can provide additional opportunities to assess how the BIT performs for occurrences other than known inserted faults. In one example cited during the study, actual failed items were collected from throughout the development and production activities and were processed through a system integration laboratory to assess the



reaction of the diagnostics to actual failures which had occurred naturally.

In the F-15 APG-63 radar, the three phases of reliability qualification and production reliability testing resulted in 38 software changes, nearly all of which were BIT improvements. The F-16 employed BIT during reliability testing to verify that it would produce consistent indications with factory acceptance test procedures.

Environmental testing can provide opportunities for identifying BIT problems, changing tolerances, and modifying voting criteria. It should not be used as a demonstration tool, in part because of the limited sample of serial number assets and fault occurrence as well as the type of faults encountered (infant mortalities and design deficiencies which are likely to be fixed). The use of reliability tests for BIT maturation should be encouraged.

Fault insertion and maintainability demonstration tests usually result in a successful verification of BIT FD/FI requirements. Since these demonstrations are usually followed by significant BIT problems in early field testing, one school of thought is to do away with these demonstrations as a waste of time and money. It is necessary to review the benefits and limitations of such demonstrations before dismissing them.

There are benefits to FD/FI demonstrations as they are currently conducted. They force the diagnostic design to mature sufficiently by a required time in the development cycle so as to pass the contractual demonstration requirement. Secondly, they force a disciplined and structured consideration of BIT characteristics (FD/FI) which is useful operationally as well as being measurable in a contractual sense. Without this motivation, one might anticipate the possibility that diagnostic design would lag performance even further. Thus, without some better motivation, they should be considered necessary.

Though necessary, they are not as effective as they could be. Fault insertion tests have some major flaws in the way faults are selected. The candidate fault list is only a small sub-set of the total known faults which could be introduced. Since it is based on predicted failure modes and frequencies, total population of interest is only as good as the FMEA. Since the FMEA does not adequately address false alarms and their causes, the demonstrations are not likely to encounter many of the diagnostic problems observed in the field. The fault selection process is also influenced by the desire to not insert faults that would damage the equipment. Therefore, the chosen faults are simple to install; e.g., shorting something rather than unsoldering, or avoiding inducing faults in expensive parts. This tendency can result in an unrealistic bias toward the set of simple failures, avoiding those that are difficult and expensive to prepare.

While fault insertion demonstrations do not provide a complete answer, they have the potential for expansion to a level where many diagnostic problems can be resolved during full-scale development and before the system is deployed in the operational environment.

#### 4. Operational Test/Maturation

Early operational testing on the F-15, F-16 and F/A-18 radars (and many other subsystems and programs) has been characterized by the discovery of high BIT false-alarm rates (including high "cannot duplicate" and "bench check serviceable" rates), diagnostic system immaturity, numerous software iterations, long troubleshooting times and lower rates of fault detection and isolation than had been expected (based on the specifications and maintainability demonstrations). Depending on the particular program and the severity of the problems, a variety of actions were taken to recover. In some cases, an ad hoc logistics support structure had to be created and overlaid on the planned logistics support concept. Workarounds were developed to compensate for BIT shortfalls. These workarounds frequently included special test aids (such as troubleshooting fault trees, breakout boxes, data bus monitors, and memory inspect devices) as well as contractor engineering support to compensate for inadequate training and technical data. The workarounds typically persisted until the BIT shortfalls were corrected or until the workarounds became institutionalized in the support structure. The E-3A surveillance radar, for example, had to pursue both correction of BIT shortfalls and institutionalizing workarounds. The F-16 went through a deliberate process of maturation to improve the built-in test. The F/A-18 is going through a similar planned maturation program for diagnostics.

One of the more severe impacts of BIT shortfalls is the lack of confidence which operational crews and maintenance technicians develop toward the BIT. This low confidence leads to poor maintenance troubleshooting practices which, once created, are difficult to overcome.

As discussed earlier, the effectiveness of demonstration testing

is limited by the manner in which faults are selected and the practical bounds of time, number of test samples and cost. The field environment provides a realistic opportunity for identifying and maturing BIT. The implication for design is that the BIT should be readily adjustable. Improvements should be able to be incorporated in software with minimal hardware impact. Contractual techniques need to be developed to plan for field maturation as a positive design technique (an extension of the design activity) rather than having the stigma of design patching.

a. F-16 (APG-66 Radar). The APG-66 diagnostics growth and maturation period spanned 44 months (May 1977-Dec. 1980) including a large overlap of full-scale development and production phase activities (see Fig. E-4). The eight configuration iterations from May 1977 to Dec. 1978 (20 months) were largely associated with growing from 45 self-tests with no BIT to the full 108 self test/BIT capability. In Jan. 1979, the first squadron was activated at Hill AFB. Pilot usage, aircraft interface and intermittent problems were an early indicator of the need for maturing the diagnostic capability. The maturation effort continued from Jan. 1979 to Dec. 1980 (24 months). Incremental changes were consolidated in ECP-331 (B++ radar) which was incorporated in production radar and retrofit in 1980. This ECP significantly reduced the occurrence of faults and CNDs (Fig. E-5 and E-6). Figure E-7 is another indicator of the improvement in detection, isolation and CND rates from development flight testing in 1978 to the FOT&E II. Though there was a significant improvement, about 47 percent of the total FOT&E write-ups were in the category of known engineering deficiencies and were not considered in the BIT statistics. This category declined significantly throughout the test (from .3 per sortie to .03 per sortie) as improvements were introduced.

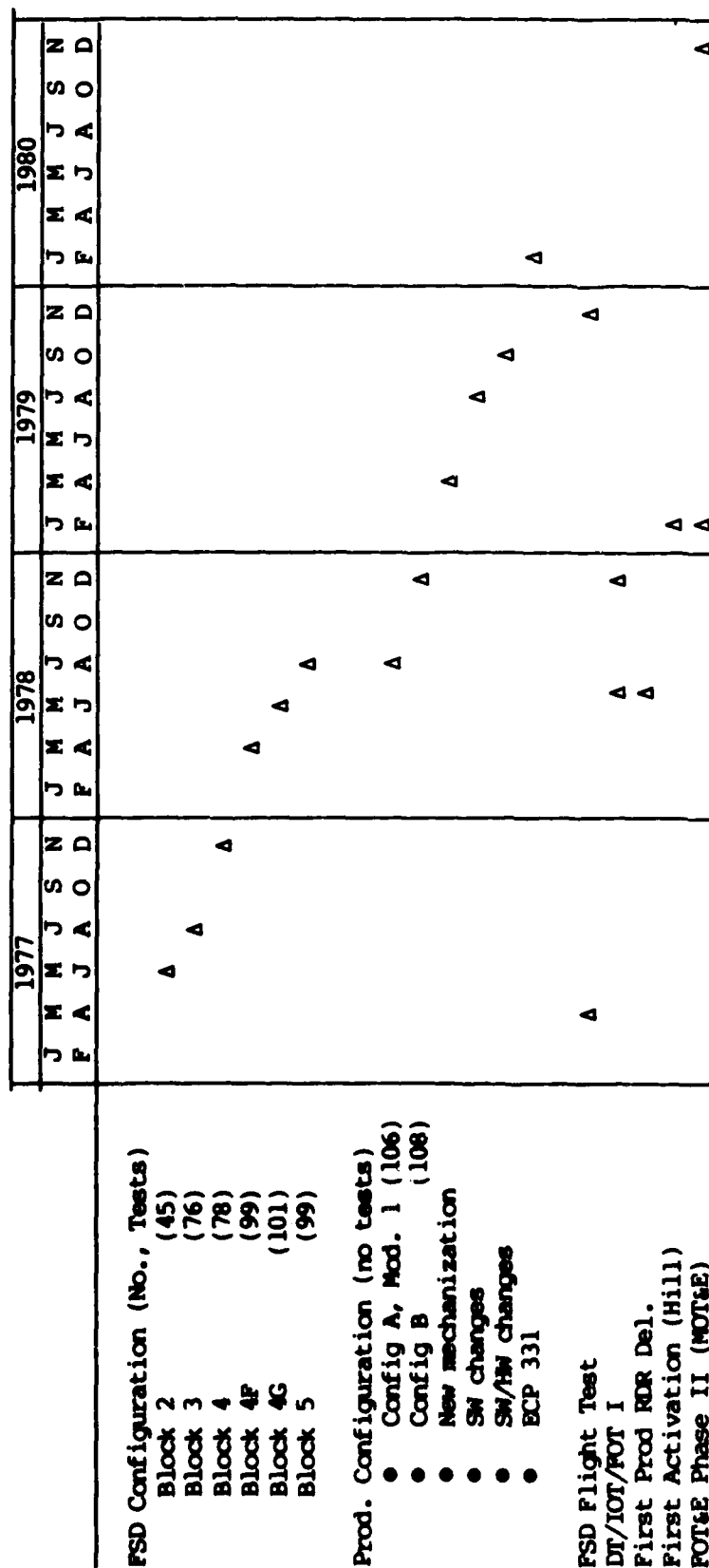


Figure E-4. AFG-66 Diagnostics Growth/Maturation Schedule

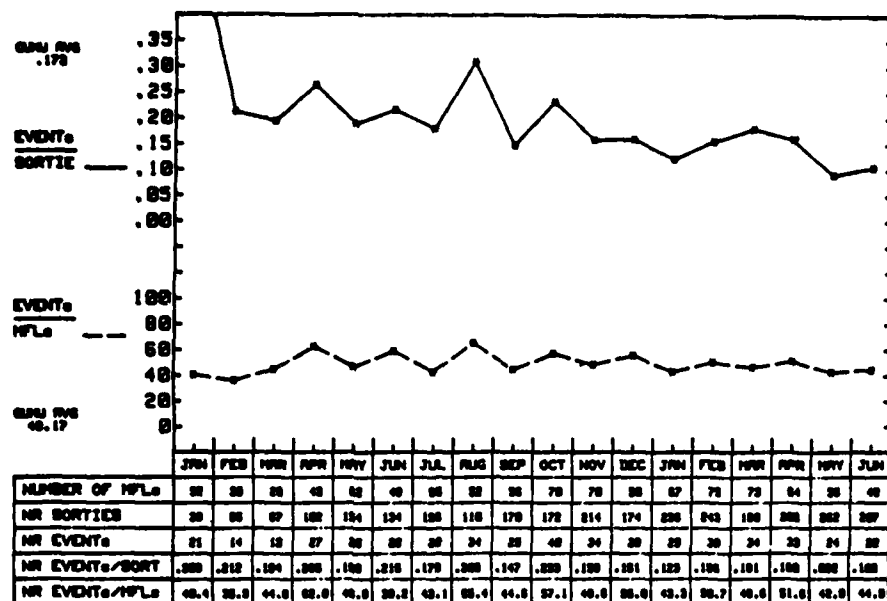


FIGURE E-5. Radar MUX-BUS Avionics Maintenance Fault List per Sortie

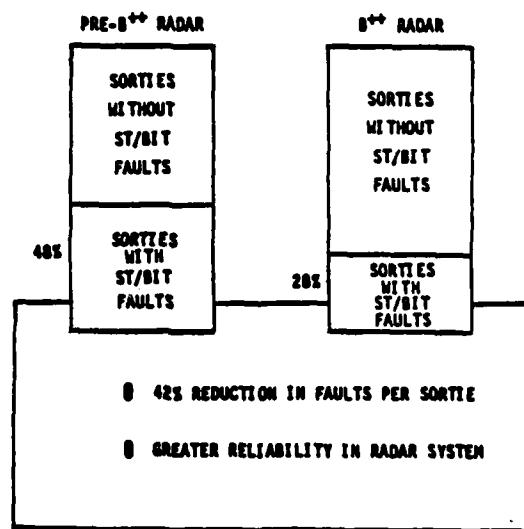


FIGURE E-6. B++ Radar Modification Effects

EVENT	DATES	NUMBER OF MONTHS	FLYING HOURS	RADAR			COMMENTS
				DETECT	ISOLATE	CND	
DT/OT BIT/ST Effectiveness AFFTC EDWARDS AFB	7 Jun 78			24-	73-	34-	5 radar versions
	to 22 Nov 78	5.5	340	40	85	60	9 OFF versions
FOT&E II HILL AFB	Jan 79	18	13,404	94	91	30	
	to Jun 80 (Dec 80)	(24)					

FIGURE E-7. Diagnostics Testing

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b. F/A-18 (APG-65 Radar). The F/A-18 has gone through a series of tests for the purpose of assessing and maturing the diagnostics capability of the aircraft systems. The event which indicated that a significant maturation effort would be required was the IOT&E conducted by the Operational Test and Evaluation Force. Specific radar subsystem data were not presented in the quick-look report. However, it did report:

- Avionics BIT is incomplete (82%)
- MMP high false alarm rate (82%)
- High initiated BIT false alarm rate for major system failures (56%)
- Low WRA BIT isolation validity (56%)
- Radar and flight control systems require the greatest level of effort to repair.

Subsequently, the Navy Bureau of Inspection and Survey (BIS) conducted trials and three phases of a BIT assessment program. Even at the end of this effort, the radar was still identified as one of the major problem subsystems (see Fig. E-8). This maturation effort is planned to continue in several steps. Follow-on BIT assessment will be conducted through Sept. 1983 on Block 7/8 aircraft. Mature BIT assessment is planned for Oct. 1983-Sept. 1984 on F-87 omnibus ECP (Block 11 aircraft). A concurrent aircraft/automatic test equipment vertical testability assessment started in Mar. 1983 and will conclude in Sept. 1984. The total effort (disregarding IOT&E) covers 34 months.

At the start of field testing, the diagnostics capability was not only immature, many tests had not really been implemented. Throughout the maturation process, there was a two-step discipline for declaring the capability of a particular test. First, the contractor had to declare the test functional (i.e., essentially ready to be assessed). Secondly, the Navy had to declare the



Event	Dates	Number of Months	Flying Hours	Avionics BIT			Remarks
				Det.	ISO	False Detect. or False Alarm	
IOT&E	27 Oct 80 28 Jan 81	3	-		56.0%		Major Problems: radar and flight control
BIS*	4 Nov 81 3 May 82	6	924	47.0	73.0	72.0	Radar is a major problem
Phase I BIT Assmt.	Same	Same	Same	73.1	95.4	50.0	Radar, displays, stores mgmt. and flt. control
Phase II BIT Assmt.	4 May 82 15 Aug 82	3.5	982	79.0 81.9	84.0 86.7	33.8 36.7	Radar, stores mgmt., flt. control
Phase III BIT Assmt.	16 Aug 82 20 Oct 82	1.5	307	82.6	68.4	42.4	Radar, stores mgmt., flt.

\*Results under avionics BIT are radar specific.

FIGURE E-8. APG-65 Diagnostics Maturation

test operational, which meant the test had to meet certain false-alarm and performance criteria. Over the whole period, the various test codes were in a constant state of flux between non-functional, functional but not operational, and operational. The radar BIT improvements are listed on Fig. E-9.

c. Electronic Warfare System. Though not a specific case for this study, an electronic warfare system provides another example of an effective maturation program. Two phases of FOT&E were conducted about two years apart. During FOT&E I, FD was low at 62 percent as a result of a 38 percent CND rate. The FI rate was 71 percent, largely because of the 19.2 percent RTOK rate. These indicators were symptoms of a larger suitability problem which included deficiencies in reliability, software, technical data, and training. The program subsequently went through an intensive maturation phase to correct these problems. The diagnostics maturation included a team of contractors and Air Force technicians at the plant who used large numbers of realistic failure modes to devise the best set of BIT functions and technical procedures. The results in FOT&E II included a reduction in the CND rate from 38 to 24 percent, an improvement in the FD rate from 62 to 76 percent, and much more importantly, a dramatic reduction in the RTOK rate from 19.2 to 3 percent.

## 5. Other Analyses

In addition to the case studies explicitly conducted for this report, other analyses which are pertinent to diagnostics were reviewed.

	<u>Effectivity</u>	<u>Character*</u>
1. 80% BIT matrix unmasked, many tests not functional, MMP 010 made nonfunctional	F-17, Tape 100	SW
2. ECP 079 reduced hangups MMP 010 made functional MMP 040-045, 052 made nonfunctional unless accompanied by pilot squawk	F-28, tape 100A	SW
3. New tape improved FD/FI and FA. 95% BIT matrix unmasked, MMP 040-045, 052 functional 3 test timing, logic changes	F-28, tape 101	SW
4. ECP 044 improved 7 I BIT test points, changed PBIT criteria for FD, improved FI (trans, R-E, antenna)	F-32, tape 101A	HW & SW
5. ECP 095 reduced time to test, improved FI accuracy reduced source of test hang ups	F-37, tape 101B	SW

\*SW=software, HW=hardware

FIGURE E-9. APG-65 Diagnostics Maturation  
Radar BIT Improvements

a. Causes of "Bench Check Serviceable" (BCS). The standard maintenance data collection system does not adequately address the reasons for a high BCS rate. Furthermore, there are many error sources in the data which make the reported BCS rate only a tentative indicator of actual field experience.

In addition to the RADC report on causes of false alarms (referenced in para. 1 above), two other studies shed some light on the factors which cause unnecessary removals. The F-15 Avionics Maintenance System Task was conducted by McDonnell Aircraft from Aug. 1979 to Apr. 1980 to identify the sources of "Bench-Check Serviceable" (BCS) on specific avionics Line Replaceable Units (LRU). The purpose was to recommend means to eliminate or reduce BCS loading of intermediate level automatic test equipment. A field study was conducted at Holloman AFB during which time 222 LRUs were processed. There were 58 BCS actions. The BCS rate of the sample was either 25.3 percent or 30.4 percent, with the uncertainty created by data recording problems (LRUs coded BCS which were in fact repaired, and units where the action taken was unknown). Figure E-10 is the study assessment of the direct and indirect contributors to the BCS actions. The field environment clearly introduces a multitude of factors which can produce a BCS action. Furthermore, the maintenance data collection system gives little insight into these factors. At best, it indicates that there might be a problem, but provides no information with which to identify the causes.

FACTORS	NUMBER OF CASES (Total 58 BCS)	
	Direct Contributor	Possible Contributor
Technical Orders	6	5
Technician Training	--	38
Operator Training	5	--
Maint. Mgmt. and Opns.	26	22
Built-in-Test	--	8
Automatic Test Equipment	--	1
Supply/Spaces	--	--
Personnel (Qty. and Skill)	1	--
Flight and Shift Schedules	--	9
Reliability (Intermittents)	--	15

Figure E-10. F-15 Avionics, Causes  
of 58 Bench Check Serviceables

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The second effort was RADC-TR-83-2, Jan. 1983, entitled "Study of the Causes of Unnecessary Removals of Avionic Equipment," performed by Hughes Aircraft Company. The field survey was conducted at 12 bases and 3 depots; it involved six selected avionic equipments used on ten different aircraft platforms. The average unnecessary removal (UR) rate (same as BCS) was 32.7 percent. The UR rate on the same equipment, but different platforms, varied from zero percent to 80 percent. For the same equipment and platform, but at different bases, the UR rate varied from 37 to 76 percent. The causes of URs varied significantly with the specific equipment, as one would expect. The overall sample assessment of causes is listed in Fig. E-11.

<u>CAUSE</u>	<u>% OCCURRENCE</u>
Ineffective Built-In-Test	22
Ineffective or Missing Test Equipment	18
Ineffective Supervision/Support	16
Ineffective Technical Orders	13
Inaccessibility	12
Management Directives	7
Test Equipment Differences	7
Inadequate Skill	5
Inadequate Feedback	1

FIGURE E-11. RADC/Hughes Assessment of Unnecessary Removal Causes

These studies looked at equipment which was fielded and, in general, well beyond the development phase. Several conclusions can be drawn:

- a. Once a system is fielded, it takes a special field survey effort to understand (and for that matter, accurately estimate) the BCS problem.
- b. The corrective actions required to resolve BCS problems in fielded systems are not evident without such a field survey.
- c. The operational environment introduces a variety of cause factors which are not well understood or anticipated in the design process.

A possible implication for design is that the more effective the front end design and maturation processes are to reduce the sources of ambiguous indications, the lower the field BCS rate will be. The study results also suggest that an integrated approach to diagnostics may be useful. Maintenance policy, technical data, training and personnel skills are all factors which interact with BIT, ATE, and vertical testability to produce an operational maintenance capability.

One of the specific LRUs in the UR study was the radar data processor (WUC 74FQ0) from the APG-63 radar. 508 removals occurred and 266 (or 52 percent) were considered unnecessary. Ineffective built-in-test was judged the most frequent UR cause (45 percent). The breakout by base and cause is indicated in Fig. E-12.

<u>BASE</u>	<u>O LEVEL LRUs REMOVED</u>	<u>I LEVEL TOTAL URs</u>	<u>UR RATE (%)</u>
1	125	95	76
2	193	90	47
3	157	58	37
4	<u>33</u>	<u>23</u>	70
TOTAL	508	266	52%

<u>CAUSE</u>	<u>URs</u>	<u>CASE RATE (%)</u>
Ineffective Built-In-Test	119.8	45
Test Equipment Differences	66.8	25
Skill Level Inadequate	30	11.3
Inadequate Supervision/Support	<u>49.3</u>	<u>18.7</u>
	266	100

FIGURE E-12. APG-63 RDP Unnecessary Removals  
And Causes



b. Impact of Diagnostic Capability. Other sections have discussed the problems associated with defining, specifying, designing, demonstrating, and collecting field data on diagnostics figures of merit.

A related problem is the criteria associated with assessing a figure of merit. Is 95 percent fault detection enough? Does an O-level CND rate of 30 percent really impact the ability to perform the mission? Is a RTOK (BCS) rate of 15 percent a more serious problem than 30 percent CND? Which should be fixed? The designer and the operator would both like to know the answers to such questions. In the context of a specific weapon program, with a significant analytical effort, some limited answers are possible. However, neither the tools and techniques nor the data for answering these questions are "on the shelf" for easy assessment and trade-off of various levels of diagnostic capability. The questions are even more difficult to answer in the generic case. The following discussion offers some suggestions for thinking about the answer.

Level of Automated Fault Detection (FD) - The answer is that enough data is needed to tell the operator that a reasonable system capability is left to achieve a high probability of mission success. He needs to know the capability of essential mission functions. If the system is fault tolerant and redundant, enough FD to automatically reconfigure the system must be provided to accomplish the mission. The presentation of information to the aircrew is a human factors trade-off. Presenting more information than the operator can handle ambiguously could just as easily jeopardize mission success as could too little information. In any case, the indications have to be reliable to keep a high level of crew confidence. Quantifying "enough but not too much" is a complex task.

RADAR	CND RATE (#CND/#MA) (%)	CND FREQUENCY (PER 1000 FLYING HOURS) IMMATURE MATURE	MEAN TIME TO REPAIR (HOURS)			MAN HOURS PER MA
			ALL MA	FAILURES	CNDs	
F-15 A-D APG-63	39-42	(140) 57	*	*	*	3.6 - 10.2**
F-16 A/B APG-66	48-51	(48) 29	1.5-2	*	*	2.5 - 7.0** 2.5 - 7.0**
F-18 APG-65	36-52	36 -	1.3	1.5	1.2	2.3

\* Not available from data system

( ) Estimates, not available from data system

\*\* Range indicates values for lowest and highest LRUs

FIGURE E-13. Radar CND Rates, Frequencies, and Repair Times

The fault detection requirements for the maintenance technician are somewhat different. Where the aircrew may need information in terms of seconds, the maintenance crew needs are more in terms of minutes. The need for non-ambiguous information is just as important, however.

Fault Isolation (FI) - Provides the maintenance personnel the capability to deal with detections and effect accurate, rapid repair actions. Fault detection requirements suggest a functionally-oriented mechanization. A different mechanization approach may be necessary to isolate discrete units for replacement. In fault tolerant and redundant systems, the technician needs insight into all the paths which need repair. Since an airborne fault may be environmentally mission induced, it may not be possible to duplicate on the ground. In this case, the system will have to remember why the failure occurred so that the malfunctioning unit can be replaced. This knowledge must be preserved so that the unit can be repaired in a field shop or depot. If not, it will contribute to the RTOK rate.

CND Rate - The CND rate can be viewed on the basis of maintenance actions or on the basis of occurrences per sortie. A CND rate of 50 percent (1 out of every 2 maintenance actions) sounds excessive. However, a 50 percent CND rate can mean dealing with one per five sorties or one per 50 sorties. Obviously, the occurrence on a sortie basis is a much more meaningful parameter.

The mission impacts of CNDs are twofold. First, the end item is down (unavailable for another mission) until maintenance can be performed. Secondly, they consume maintenance resources (available manhours). On the average, a CND maintenance action takes less time to repair than a fix action. Figure E-13 is a comparison of the airborne radar CND rates, frequencies, and associated repair times. Though mean times to repair are relatively short, these are only the active maintenance times. Every time a maintenance action occurs, whether it ultimately turns out to be a confirmed

failure or CND, the aircraft also experiences the downtime associated with the scheduling and dispatching of a maintenance crew. In the case of the F-18 radar, the awaiting maintenance factor per maintenance action is 4.8 hours.

In a surge situation, considerably more delay time might be envisioned because of the additional maintenance demands of a high-sortie generation schedule.

There are several conclusions to be drawn from Fig. E-13. In the case of these three radars, a significant number of in-flight discrepancies cannot be duplicated on the ground. Though cannot duplicate actions probably take less time than verified failures, their frequency, time to repair, and the fixed time penalty for awaiting maintenance do impact aircraft availability. One can judge the usefulness of CND rate versus flying hour frequency as measures by contrasting the F-15 and F-16 radars. The F-15 has a better (lower) CND maintenance action percentage than the F-16, but it also has far more CNDs per 1,000 flying hours. One would expect the impact of a high CND rate to be worse in a wartime situation than in a peacetime training profile.

Air Force data collection systems suggest that CNDs are a major maintenance problem, particularly in complex electronic subsystems such as fire control. On a survey of four different aircraft fire control systems, CNDs accounted for 40 to 70 percent of the fire control maintenance events and 30 to 50 percent of the fire control maintenance manhours.

Bench Check Serviceable (BCS) Rate - Like CNDs, a high BCS rate adversely impacts aircraft availability and maintenance resource consumption. The impact on aircraft availability is less direct, however. It only begins to directly impact aircraft availability when all available spares in supply have been issued. Besides using available manhours as do CNDs, BCSs also consume intermediate-level test station time. A higher induction rate of units which eventually check serviceable also means a higher probability for a

backlog of units awaiting test station time. Like CNDs, BCS should not just be viewed as a rate of units processed; the more meaningful measure of the impact is in terms of occurrences on a flying-hour basis.

Figure E-14 depicts the BCS rates, frequency relative to flying hours, and time and manpower factors. Some tentative conclusions are possible. Nearly one of every four units processed in the shop has no defect found. The mean time to repair, though longer than O level CND times, is only a part of the penalty for incurring a BCS. A typical LRU spends 3 to 5 days in the base repair cycle pipeline. Unnecessary removals consume man hours in the shop as well as loading the test stations and decreasing the availability of spares. It is difficult to estimate the direct impact of BCSs on aircraft availability. In general, a high BCS rate would have a greater impact on aircraft availability during a surge scenario.

It is interesting to note that the Air Force methodology for computing replenishment spares quantities does not include BCSs. Spares are replenished only on the basis of units actually repaired in the shop. Thus BCSs do not increase the number of spares in the system, but they do increase the utilization (and outage) of the ones which are in the system, as well as creating the need for cannibalization when base level stocks are depleted.

Repair Times - Assessing the impact of BIT on repair times is straightforward in theory but difficult in practice. Normal maintenance data collection systems do not distinguish whether troubleshooting (fault isolation) is performed through BIT (automated or semi-automated) or through manual techniques or a combination of the two. Results from a few special tests provide some insight into the contribution of BIT to the overall mean time to repair. In one Air Force operational test of an electronic warfare system, such measurements were made. The Mean-Time-to-Repair (MTTR) model was partitioned into five parts: Set-up of Ground Support Equipment

RADAR	BCS RATE (#BCS/#UNIT PROCESSED)	(PER 1000 FLYING HOURS) IMMATURE MATURE	MEAN TIME TO REPAIR ALL MA FAILURES CNDs	MANHOURS PER UNIT PROCESSED
F-15A/B APG-63	27-38	* 30	(6-8) * *	7.6-14.3
F-15C/D AIG-63	21-26	*	(6-8) * *	10.1-11.2
F-16A/B APG-66	24-28	* 5	3.3-8.9 * *	.7-3.2**
F-18 APG-65	16-28	16	6.4 6.7	7.7

\*Not available

\*\*Probably not good test data due to RIW

( ) Estimate

FIGURE E-14. Radar Bench Check Serviceable Characteristics

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(or AGE), troubleshooting, repair, verification, and teardown, as well as for maintenance actions of the AGE. The MTTR was then computed for CND maintenance actions which resulted in a repair. The latter were broken down by troubleshooting method: automated, semi-automated, and manual. From Fig. E-15, it is apparent that the variation in MTTR for the different modes is strictly a function of the troubleshooting time which ranges from 1.3 hours automatic to 2.9 hours manual. There are obvious benefits for end item availability and manpower consumption when the BIT does the fault isolation. In this particular test, 24 percent of the 324 detections were CND. Of the remaining 76 percent where corrective action was required, 51 percent had to be manually isolated, resulting in the longer repair times. From the standpoint of improving availability it would be advantageous to maximize the number of failures isolated by BIT and reduce the manual troubleshooting requirements.

The F/16 FOT&E analyzed measured repair time for automated and manual troubleshooting for two categories: flight controls, and multiplex bus avionics. For flight controls, the BIT MTTR was 3.63 hours; the manual MTTR was significantly longer: 11.07 hours.

If the BIT had been ineffective, it would have driven a very long overall MTTR. However, it was effective for 92 percent of the maintenance actions; only 8 percent were manual. The result was a cumulative MTTR of 4.26 hours.

For the multiplex bus avionics, the spread between BIT and manual MTTRs was not so dramatic: 2.05 hours BIT versus 2.71 hours manual. The BIT was effective for 84 percent of the maintenance actions for a cumulative MTTR of 2.16 hours.

### c. General Conclusions.

- (a) BIT is necessary for fault detection and isolation, particularly in complex electronic systems.

MTTR CND (1.2) HOURS

1.2 hrs
---------

MTTR AUTOMATIC MODE 3.9 HOURS

Age	Troubleshoot	Repair	Verify	Age
.4 hr	1.7 hrs	1.2 hrs	.6 hr	. hr

MTTR MANUAL MODE 5.5 HOURS

Age	Troubleshoot	Repair	Verify	Age
.4 hr	2.9 hrs	1.2 hrs	.6 hr	.4 hr

MTTR ALL MODES INCLUDING CNDs 2.7 HOURS

2.7 hrs
---------

Figure E-15. EF-111A Peculiar Subsystems Diagnostics MTTR



- b. In general, when BIT is effective for fault isolation, it has the potential to significantly reduce repair times.
- c. When BIT fault detection errs in the direction of high erroneous detections it can adversely impact mission performance by affecting crew workload. It also contributes to downtime and maintenance manpower consumption. On a 1 for 1 basis, CND is a lesser contributor to downtime than a failure which requires corrective action.
- d. CND and BCS/RTOK rates are more meaningful when computed on a flying hour (or sortie) basis rather than on a maintenance action basis (though the latter is also a useful measure).
- e. The effect of high CND and BCS/RTOK rates is probably worse in periods of high sortie generation.
- f. Once a system is fielded and tested, it is difficult (to impossible) to determine real BIT-caused CND and BCS rates, their causes, and get-well plans without field surveys. It is important to recognize that field measures can vary significantly between bases.
- g. Once a system is fielded, environmental factors (human judgment, faulty procedures, maintenance policy, training) can cause high CND and BCS/RTOK rates. The implication for design is that BIT capabilities should be so thorough, straightforward and unambiguous that they minimize the opportunity for these factors to cause CNDs and BCSs/RTOKs.

- h. Minimizing BCSs is important for a three level-maintenance concept but it is an absolute necessity for a two-level concept.
- i. A significant analytical effort is required in the design stage to optimize BIT (FD/FI, false alarms/CND/BCS/RTOK, MTTR) and the support structure (support equipment, manpower, skill, spares, technical data. Better techniques are required.

#### C. RECOMMENDATIONS FOR IMPROVING DIAGNOSTICS

During the study effort, many recommendations were presented for improving diagnostics. These recommendations address program structuring, technical and management activities, and technological opportunities. Recommendations from the first two categories are presented here in the same basic format in which Current Practice (para. B) was addressed: requirements, design, development and demonstration tests, and operational test/maturation.

From the case study activity and the numerous other studies reviewed and presentations made, it is clear that the achievement of mature diagnostics capability is the result of a process. This process encompasses both research and development activities which are not weapon program specific, as well as the entire acquisition cycle of specific weapon programs. Figure E-16 illustrates the context in which diagnostic considerations must be addressed.

Generic R&D activities have focused historically on developing performance-oriented capabilities to counter future threats. Over the years, with the realization that performance over time was an important dimension of countering threats, reliability considerations started to be introduced in this area. Only in the last several years diagnostics capabilities have begun to be considered as important activities in the world

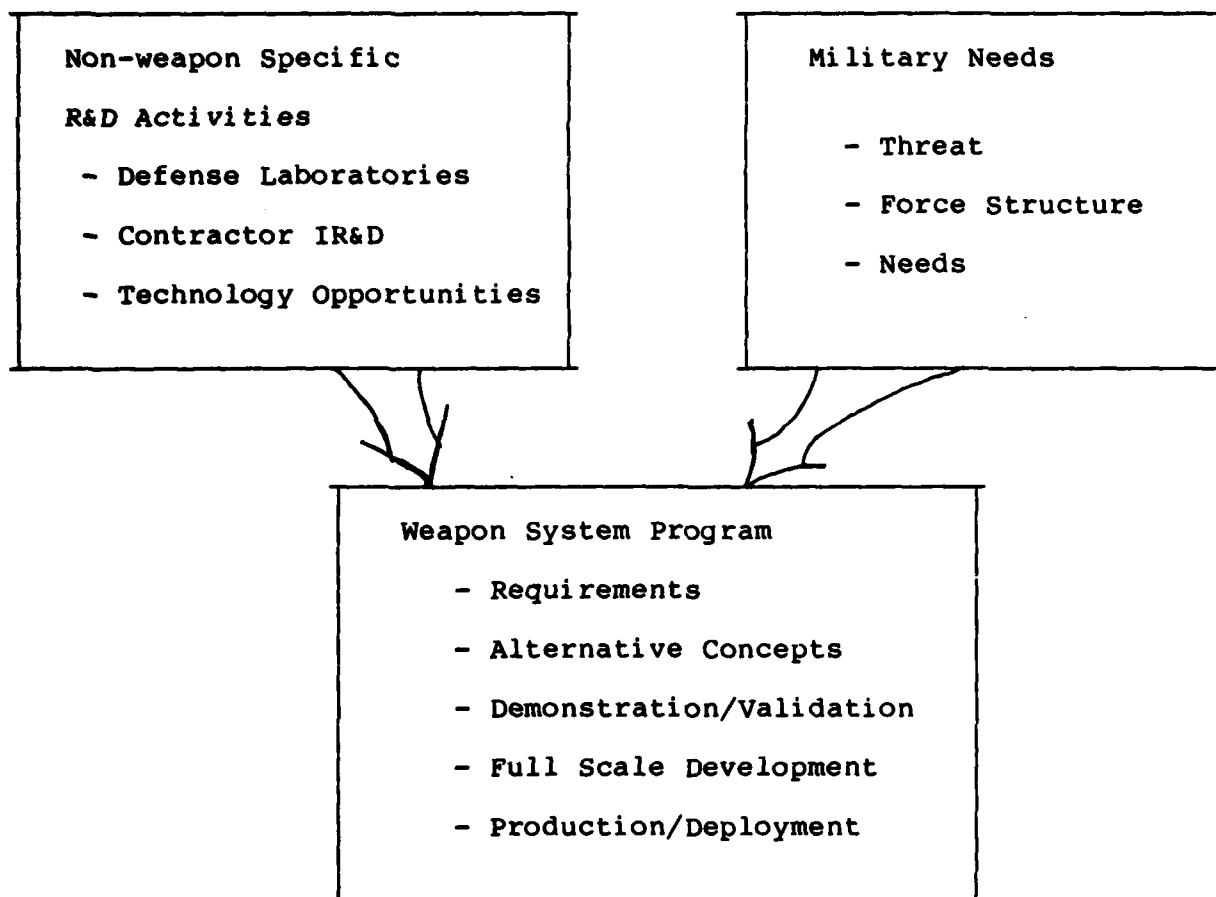


FIGURE E-16. Diagnostics Context

of non-weapon-specific R&D. It is important for DoD contractors to continue this trend so that technological solutions to diagnostic problems can evolve and, more importantly, so that technology developments focused on future threats consider how the eventual systems will be maintained.

There are a number of examples where diagnostics are being considered. The Integrated Communications/Navigation/Identification Architecture (ICNIA) and Pave Pillar programs are Air Force programs oriented toward providing advanced architectures for future avionics. They both have specific objectives to address diagnostics. The DoD Very High-Speed Integrated Circuit (VHSIC) program also has objectives to produce reliable and testable circuits. Likewise, several industry IR&D projects are developing advanced architectures and equipment which are formulated with reliability and diagnostics as principle characteristics.

The DoD needs to continue to increase this emphasis in both government laboratories and contractor independent R&D efforts. Other effects should be considered which focus on developing design tools such as computer-aided engineering techniques which enable the design of testable circuits and systems.

Referring back to Fig. E-16, military needs have evolved in recent years to considering the readiness and sustainability characteristics of force structures. All the services have developed policies to guide the development of future forces to meet the year-2000 operational requirements. These projections have in common the need for improved reliability and maintainability, reduced support tails, and better logistics C<sup>3</sup> to manage more mobile and autonomous units.

Technology R&D and military needs are providing opportunities and requirements for improved diagnostics as inputs for specific weapon system programs. From the case studies, it is apparent that diagnostic capabilities can best be achieved by focusing on diagnostics as a fundamental system characteristic.

Achieving effective diagnostics requires a plan, management strategy, motivation, technical activity, and funding which spans the acquisition activity from initial requirements definition through deployment.

#### 1. Requirements

The military user's requirements should address diagnostic capability in the larger context of the operational mission and environment as well as the support constraints of manpower, skill, maintenance concept, deployability and logistics burden. The requirements, constraints, environment and economics should then drive the architecture of the system with diagnostics as a fundamental characteristic. Significant improvements are required in formulating these requirements.

There are a number of innovative Service efforts to define requirements and development objectives for readiness and support at the front end of a weapon program. Examples include the Air Force Advanced Tactical Fighter (ATF), The Navy Submarine Advanced Combat System (SUBACS), The Army Mobile Protected Gun System (MPGS), and The Joint Services Advanced Vertical Lift Aircraft (JVX). Figure E-17 summarizes the kind of performance-driven support requirements and constraints which define the context for generating meaningful diagnostic requirements. Objectives which call for reduced levels of maintenance, high utilization rates, self-sustaining operations and reduced support tail should drive the development of high confidence built-in-test with CND/BCS/RTOK rates of near zero.

Another fundamental issue has confounded diagnostics development throughout the process; namely, definitions. Definitions, terminology and figures of merit to describe diagnostics have proliferated to the point that communication relative to diagnostics measure is difficult. This is not a trivial problem; it impedes the way that diagnostics are specified, managed, designed, tested

ADVANCED TACTICAL FIGHTER  
(ATF)

- ACHIEVE 90% MISSION RELIABILITY AT HIGH SORTIE RATE (X SORTIES IN 6 DAYS, Y SORTIES OVER 30 DAYS).
- DEPLOY THE SUPPORT FOR A UNIT IN 6-7 C-141's.
- SMALL UNIT DECENTRALIZED OPERATIONS.

SUBMARINE ADVANCED COMBAT  
SYSTEM (SUBACS)

- OPERATE FOR 60 DAYS OF COMBAT WITHOUT MAINTENANCE AND REMAIN MISSION CAPABLE.

MOBILE PROTECTED GUN SYSTEM  
(MPGS)

- ACHIEVE HIGH RELIABILITY AND MAINTENANCE SIMPLICITY TO OPERATE (INITIALLY) WITH EXTREMELY LIMITED LOG SUPPORT. (TERMS ARE BEING DEFINED).

JOINT SERVICES ADVANCED  
VERTICAL LIFT AIRCRAFT  
(JVX)

- SUSTAIN 0.90 A RATE IN WARTIME FOR 60-90 DAYS FROM UNIMPROVED SITE.
- DETERMINE INCREMENTAL DESIGN AND SUPPORT REQUIREMENTS TO SELF DEPLOY AND OPERATE AT HIGH SORTIE RATES OVER EXTENDED PERIODS.
- SELF-CONTAINED, X ACCOMPANYING A/C
- X,Y,Z SORTIES OVER 5 TO 90 DAYS

FIGURE E-17. Defining Development Objectives for Readiness and Support at the Front-End

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and measured. Proposed MIL-STD-XXX, "Testability Program for Electronic Systems and Equipment", and MIL-STD-1309 are useful but not sufficient steps to resolve this problem.

Better ways of specifying are needed to achieve the readiness and support goals of the Services. One proposal was presented which appears to have the capability of influencing reliability, maintainability, support costs, and readiness to achieve a two-level maintenance concept. The approach is to specify that all avionics line-replaceable units meet a threshold of \$XX.XX acquisition cost per removal-free operating hour. This parameter has the advantages of being operationally useful and measurable in the field but it may not communicate clearly to the designer.

## 2. Design

The following are needed:

- a. Strategies to minimize CND, BCS, RTOK and false-alarm conditions during design.
- b. Techniques to maximize vertical testability.
- c. A flexible diagnostic system so that changes can be incorporated readily in diagnostic algorithms, screens and tolerances with minimal hardware impact.
- d. Fault-free software development techniques.
- e. Techniques to enable more concurrent hardware and software development and earlier integration of the two.
- f. Trade-off tools for assessing the diagnostics implication of design decisions on the support structure.
- g. Computer-aided engineering techniques for enhancing design for testability in support of proposed MIL-STD-XXX. Some techniques such as LogMod and STAMP may already be able to meet this need though they are not used widely.
- h. Diagnostic testing in the early operational environment will reveal BIT problems. Recognize that maturation phase is a legitimate design activity and plan for it.
- i. Both the Services and contractors need to cultivate experienced groups of individuals who understand and implement good diagnostics designs.
- j. Tools for predicting, measuring, and managing the diagnostics development.
- k. Better design practices such as timing margins in high-speed circuits and systems.



### 3. Development and Demonstration Test

- a. Use reliability and other test events as opportunities to discover problems with BIT performance. Environmental testing may be particularly useful for discovering false-alarm indications such as induced intermittents and transients.
- b. Consider increasing the number of spare assets and budgeted time in the system integration laboratory so as to be able to investigate diagnostic anomalies without impacting the schedule and use of other assets.
- c. Consideration should be given to expanding the set of faults inserted to a larger set. Time required and test assets might have to increase.
- d. Consideration should be given to increasing the allowable cost of demonstrations to include repair costs, thereby permitting insertion of a better cross-section of faults.
- e. It has been suggested that computer simulation of the actual circuits can test much of the BIT provisions (hardware, software, firmware) more thoroughly and without causing damage. Consideration should also be given to building a library of computer simulation models to address the circuits available today and to keep pace with evolving technology.
- f. Comparability analysis may be useful as a method of identifying a realistic fault set for insertion.
- g. Improved demonstration techniques which better predict field diagnostics performance should be developed and incorporated in MIL-STD-471.

#### 4. Operational Test and Field Maturation

Field maturation is essential to achieve inherent diagnostics potential. The techniques and activities used to specify, design, and verify diagnostics capability do not in themselves result in a mature fielded system. When the system is first fielded, it is common to find that not all the hardware and software provisions of the diagnostics have been fully implemented. In addition, the operational use patterns and environment produce new failure modes and diagnostic indications. These new indications, which the BIT may not deal with properly, are resolved by the judgment of operators and maintainers (who may not have been trained to deal with them) and with the aid of technical data (which may not have been developed to address them). A structured engineering maturation effort in this environment is the only way to bring the diagnostic capability to its full potential. The APG-65 and APG-66 programs are excellent examples of effective BIT maturation. The key features of these programs should be used in structuring future maturation efforts for complex equipment.

The key features of diagnostics maturation are as follows:

Planning: The government program office along with the prime and key subcontractors, the user, and the operational test agency, must recognize that complex systems require diagnostics maturation in the operational environment. This recognition must be coupled with commitment, funding and a management plan to pursue diagnostics maturation until a mature capability is clearly demonstrated in the intended operational environment. The schedule for this effort is dependent on many factors. The APG-66 took 20 months to grow to full test implementation and was followed by another 24 months of maturation. The APG-65 schedule spans 34 months.

Data Collection: A special diagnostics data collection and analysis system is required to capture information on occurrences and causes in enough detail to provide a credible data base for developing and implementing engineering solutions. Navy 3M and

Air Force MDC are not sufficient but can be useful for this purpose. Other inputs include the specific indications and circumstances logged by the aircrew/operator, a BIT debriefing of all missions, the specific indications of detection and methods of isolation, a specific serial number track of LRUs/WRAs through the ultimate repair action and subsequent performance after repair, as well as the elapsed time for each element of the maintenance event (set-up, troubleshoot, repair, verification, teardown). Analysis can then focus on the causes of alarms, CNDs, BCSSs, no detects and lengthy repair times.

Recorders: If the system does not have built in capability to capture the detailed environment and condition information at the time of failure indication, additional sensors and recorders should be installed on the system during the maturation phase to provide this information.

Engineering Manpower: Knowledgeable design engineering personnel are essential at operational locations to observe and analyze the performance of diagnostics capability so that problems can be recognized quickly in the context of all the operational environmental variables.

Maintenance Manpower: A team of operational maintenance personnel (user, supporter, tester) must be available and motivated toward the objectives of maturing the diagnostics and institutionalizing preferred troubleshooting procedures and maintenance policy.

Operational Support: The operational entity which is employing the new system must be charged specifically with supporting diagnostics maturation and must not be so overtaxed with training commitments that it cannot dedicate sufficient resources to support maturation activities. When a system fails or exhibits a diagnostic problem of interest to the maturation team, the emphasis should be on fully exploiting and understanding the cause of the problem rather than hurrying the system back into commission

to meet a mission-capable rate or training commitment. These operational units must have sufficient assets assigned to meet both operational and maturation requirements.

Data Base Resources: Sufficient computer resources (time, access, programming) must be available at the operational location to maintain a diagnostics maturation data base and to support timely analysis by the maturation team.

Software Discipline: Since many BIT anomalies are corrected by software changes, a vigorous software data collection and tracking effort is required to update and control the software configuration. Though this activity is normally conducted at the contractor's facility, it must interface closely with the field maturation effort. The APG-66 went through at least eight block configuration changes and one major ECP during maturation. The APG-65 had five tape configurations in the first 20 months of maturation.

Contractor Support Base: Contractor resources (time, engineering manpower, and system integration laboratory/software support facilities) are required as a support base for the field engineering activity. These resources are necessary for verifying field anomalies as well as formulating, testing and implementing diagnostic corrective actions. Production testing activities at the factory may present other opportunities for observing additional failure modes and diagnostic indications. These opportunities for diagnostic improvements should be used to supplement the field maturation activity.

Contractor Use of Diagnostics: The contractor must be required to use the BIT, diagnostic procedures, and technical data being developed for Service use whenever he is performing maintenance; for example, during early flight testing and interim contractor support. These events can present early opportunities for maturation, even before operational testing starts.

## 5. An Approach to Planning Future Avionic Diagnostics

The following section is presented to illustrate how a system might be structured at the front end to achieve significant diagnostic improvement. It is only one possible approach to the solution. It is specifically oriented toward avionics but the thought process should be useful for other applications as well. Regardless of the system type, diagnostic capability must be considered as a fundamental concern in the conceptual system architecture.

In the world of avionics diagnostics, bold steps are necessary to improve performance radically in the field and substantially reduce the cost of maintenance. Supportability improvements, particularly the contribution of avionics diagnostics, must take on a new approach to solve the problems faced by the Services in the field today. Technology improvements clearly offer the opportunity to make strides toward such improvement. Advanced architectures provide the means to achieve improved supportability.

At the outset, system improvement objectives should be established to significantly improve supportability. The context for these objectives is formed by improved requirements definition as discussed in paragraph C.1 above. Some more specific goals are listed below:

### SYSTEM IMPROVEMENT GOALS

- Malfunctions which Cannot be Duplicated (CND) by maintenance personnel not to exceed X per 100 flight hours.
- Bench-Checked Serviceable (BCS) or Retest OK (RTOK) events not to exceed Y per 100 flight hours.

- Maintenance to be accomplished by personnel having no higher skills than the skills of today's personnel.
- Capability of autonomous, self-sufficient combat operation at dispersed sites with no avionics intermediate shop (AIS).
- Built-in diagnostics, health-monitoring and fault-management functions with advanced capabilities.

One method which has been suggested to achieve these and other goals is documented in the General Dynamics Advanced System Integration Demonstration report which was developed under the Pave Pillar program.

This concept takes a new approach to what a Line-Replaceable Unit (LRU) is for removal and replacement maintenance actions at the aircraft level. Smaller, less-expensive LRUs are defined for use in advanced packaging concepts. Each LRU is self-sufficient with regard to diagnostics. The concept is depicted in Fig. E-18.

This approach requires the application of new technologies and could ultimately result in significant cost reductions in supportability of weapon systems. The required technologies and concepts are listed in Fig. E-19.

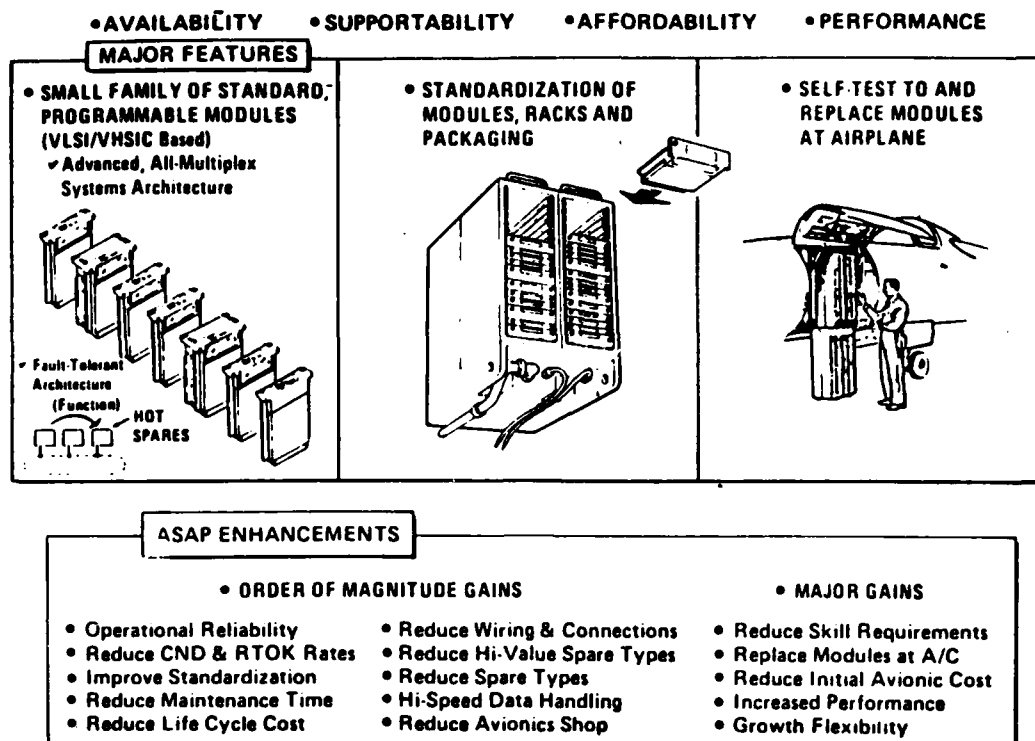


FIGURE E-18. Advanced Avionics Architecture  
for Major Improvements

- VHSIC technology
- Modularity/module level self-test
- Two-level maintenance/line replacement
- Fault tolerant architecture
- On-line spares
- Self diagnostics
- Expert systems diagnostics

FIGURE E-19. Technology and Concepts for  
Reliability/Maintainability/  
Supportability Improvements

A key to this new architecture is the recognition that many functions performed by various avionic subsystems are indeed common, particularly in digital functions. Figure E-20 illustrates how avionics subsystems can be partitioned into common functions.

AVIONIC SUBSYSTEM / COMMON FUNCTIONS	$\mu$ C	A/D	D/A	A/D D/A	D/ DES	DES/ D	FREQ/ D	MM	PS	MUX
FCS	✓	✓	-	✓	-	-	-	✓	✓	✓
ENGINE	✓	✓	✓	✓	✓	-	✓	✓	✓	✓
ECS	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
AIR INLET CONTROL	✓	✓	-	✓	-	-	-	-	✓	✓
AIR DATA AND MOTION SENSORS	✓	✓	-	-	-	-	-	-	✓	✓

FIGURE E-20. Avionic Subsystems Can be Partitioned into Common Functions



Figure E-21 shows common module design approaches to the different types of common functions performed within avionic system elements.

The key features of this approach are:

- Groups of common modules constitute traditional subsystems
- Communication within subsystems over high-speed parallel bus
- Communication within subsystems over serial bus
- Extensive self-test capabilities
  - Test processor in each cluster
  - System-level maintenance processor
- Integrated airplane racks
- Directly usable in airplane and ground systems.

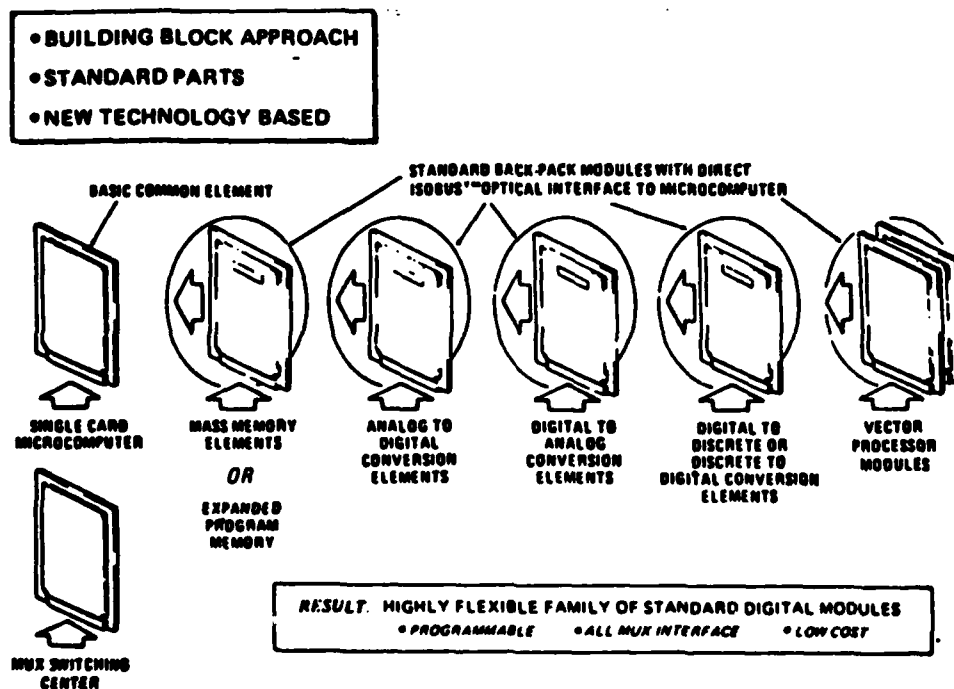
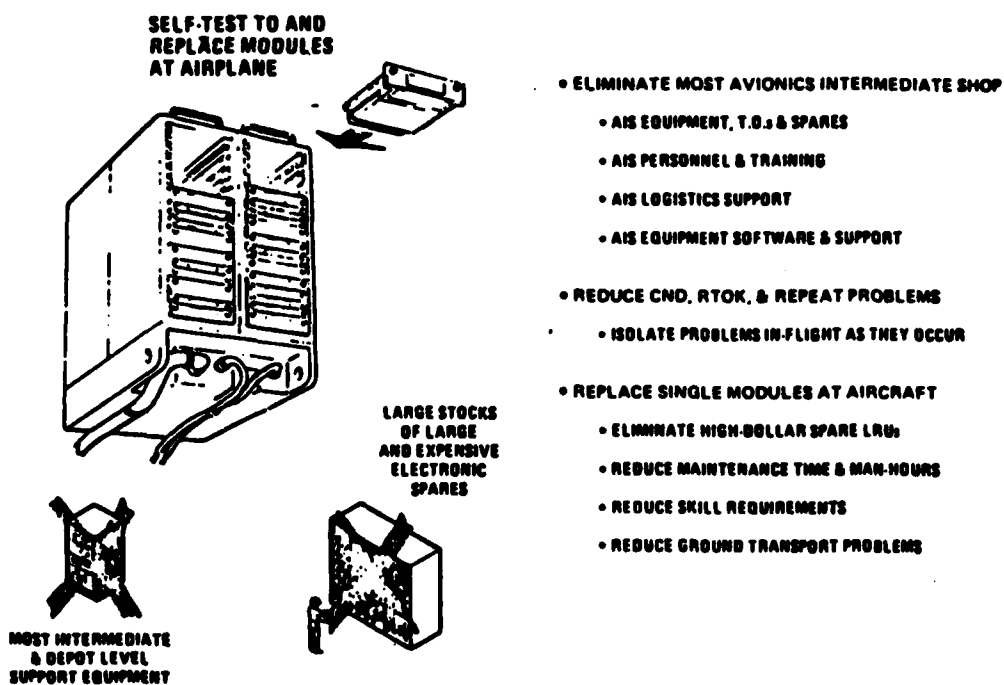


FIGURE E-21. Common Functions Can Be Performed By Standard Modules

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The method suggested to achieve a two-level maintenance concept depends on self-test that is self-contained and comprehensive within individual modules. Common module design with these attributes is achievable through VHSIC and advanced architectures. Figure E-22 shows how this approach uses an integrated rack for the modules and lists the expected benefits.



**FIGURE E-22. Automatic Self-Test to Single Module Will Revolutionize Support**

Commonality of modules among avionic subsystems obviously has significant cost reduction implications. Figure E-23 shows potential reductions in spares costs of well over 60 percent.

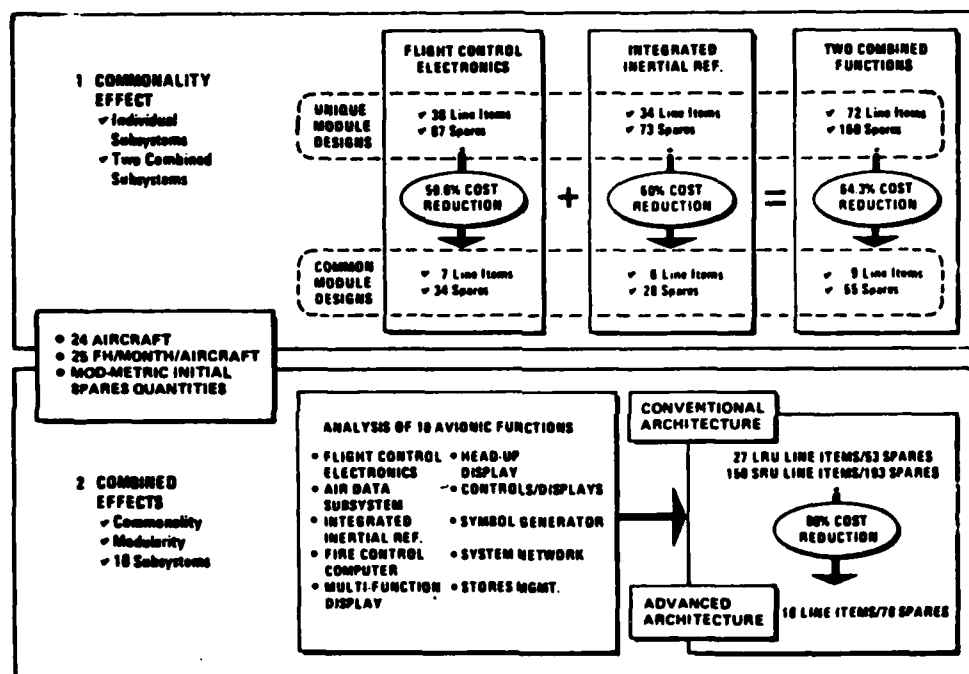


FIGURE E-23. Commonality and Modularity Reduce Spares Costs

A summary of this approach and its potential gains in supportability are shown in Fig. E-24.

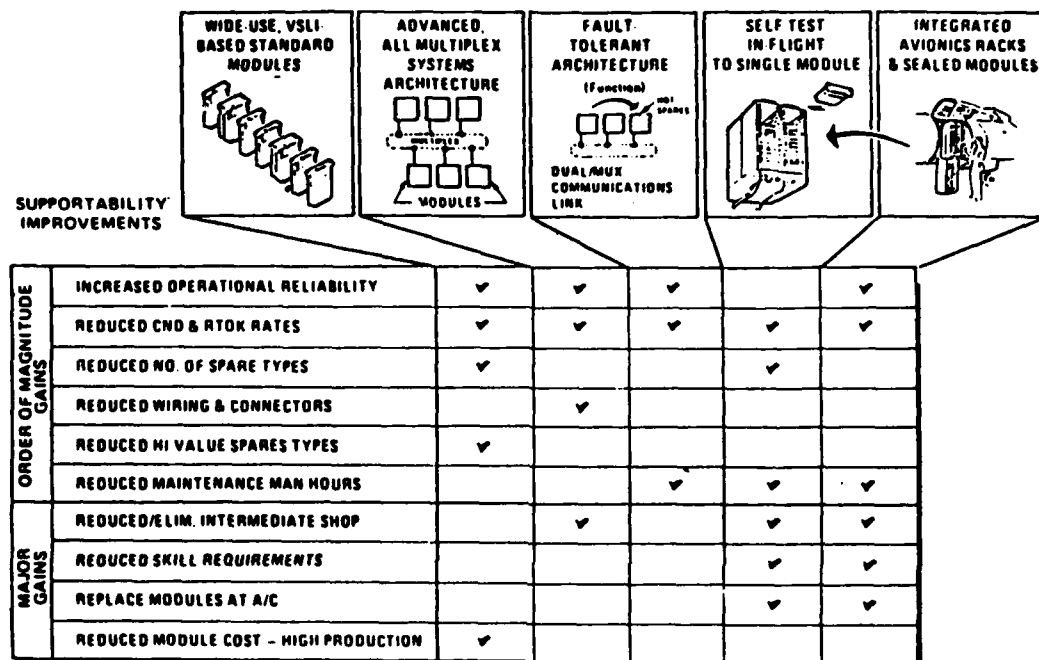


FIGURE E-24. Summary Overview of New Avionics Approach

The potential payoffs of this approach can be substantial in the areas of reduced cost for spares and maintenance hours and at the same time provide higher system availability.

- Reduced system cost
  - Fewer module type
  - Larger production quantities
  - Less support equipment
  - Fewer spare types
  - Less maintenance personnel
  - More commonality
- Higher system availability
  - Increased reliability
  - Quicker turnaround
  - Improved off-site deployment
  - Affordable spare level

A systematic approach to new technology programs is required to improve diagnostics and fault management, achieve reductions in support cost, and improve the readiness and sustainability of weapon systems. A recommended approach is to:

- Establish an umbrella DoD laboratory program for diagnostics.
- Establish R&M programs to reduce unnecessary maintenance to near zero for current and future weapon programs.
- Develop special diagnostic hardware; for example, non-volatile memories for "soft" failures.
- Focus on future performance-driven support requirements.

- Develop industry standards for design practice; for example, design margins for timing functions.
- Demonstrate diagnostic R&D projects in an operational environment.
- Collect and analyze field data and current systems to better understand problem causes.
- Include diagnostics as a basic consideration in R&D programs which are oriented to advanced system architectures, hardware and software.

APPENDIX F

KEY R&M ISSUES

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## APPENDIX F

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## A. AFFORDABILITY

During past years, many tasks have been undertaken to identify the cost of Reliability and Maintainability for typical weapon system programs. Even though senior management within the Department of Defense remains interested in capturing the costs associated with discrete reliability and maintainability activities, there is no evidence that a work breakdown structure (WBS) change has been made to require the collection of cost in a manner that would support this desire.

Currently, the costs of reliability and maintainability activities are contained in varying amounts throughout the typical WBS as shown in Fig. F-1 below for aircraft systems.

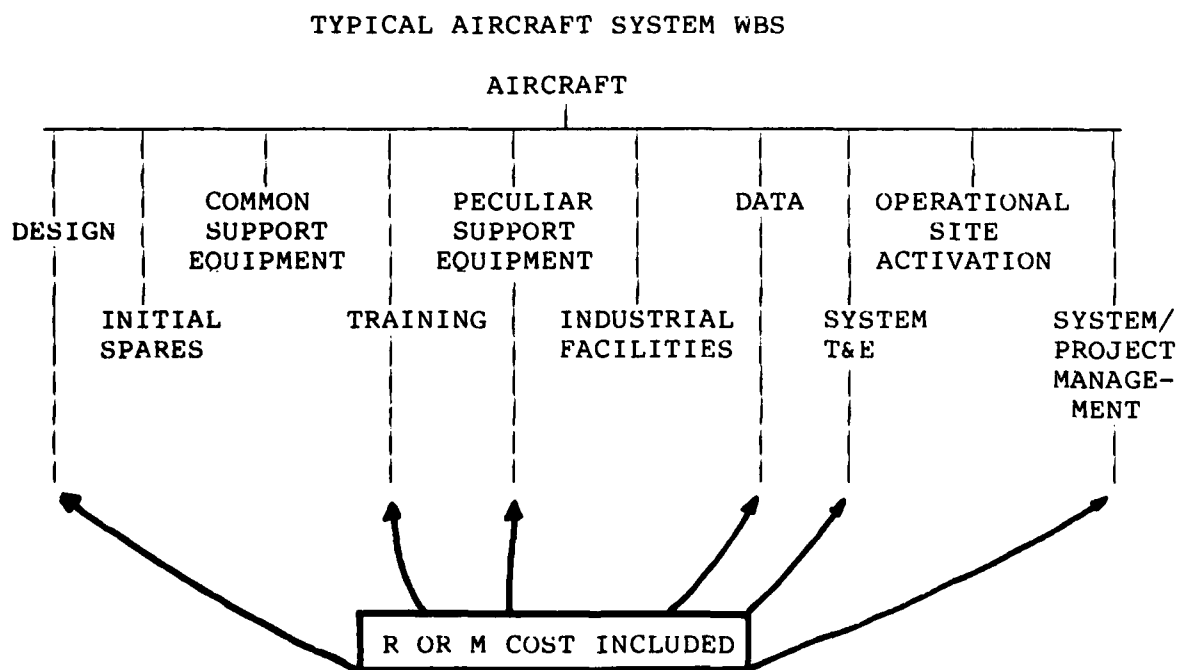


FIGURE F-1. Relating R&M costs to a WBS

Even though the WBS has not historically provided the necessary detail to allow the dissecting of costs associated with R&M, the desirability of doing it remains. Throughout the course of the case study development and analysis, efforts have been made to collect the costs associated with particular R&M activities. In a limited number of cases cost data have been collected. Case histories document cases of reduced life-cycle costs (LCC) associated with the performance of a specific reliability activity. In other cases it was possible to identify that the absence of certain reliability or maintainability activity has led to supportability problems once the system was fielded.

The cost of a typical reliability and maintainability program is composed of both fixed and variable components. Even though decisions to do more or less of a specific activity are normally based on the marginal cost associated with a expected benefit, it is not desirable to structure an entire R&M program based on anything other than a balanced program. Tasks performed that lead to a more reliable or maintainable system are strongly interrelated. For example, if black-box level screens were 100 percent effective, lower-level screens at the subassembly and part level could be reduced without significant impact on field reliability. However, due to the differences in costs of repairing failures at different levels of assembly, this approach would have a different cost for repair than a coordinated screening program which screens out failures at the most cost-effective level, i.e., part, sub-assembly, black box or system. With that in mind, we have begun our evaluation of the affordability of R&M with a look at the baseline costs associated with programs of differing sizes and complexities to define the resources that a program might consume in manpower-related activities. For some typical program tasks like analysis, the total resources

required may be directly related to manpower. For other tasks such as testing, the cost components might include manpower, facilities and the hardware to be tested.

Following the evaluation of the baseline costs of R&M, the discrete costs of select activities that are performed for improving reliability and maintainability are evaluated for payback associated with those activities. The analysis looked specifically at the costs of: maturation testing, focusing primarily on the APG-65, the APG-66 and the T700; typical Environmental Stress Screening (ESS) programs; and MIL STD versus commercial parts in terms of the implications associated with part quality and cost and the maintenance costs associated with CNDs and RTOKs.

#### 1. Baseline Costs for R&M

The objective of the program case studies has been to develop a credible list of engineering, design, test and contracting activities which if followed will: improve R&M levels, be predictable in cost and schedule, be discernible in terms of effect on equipment design, be relatable to pay-offs in reducing support cost, improving readiness, and be effective in accelerated acquisition (concurrent) programs. Other sections of this case study analysis address portions of this objective while this section establishes a baseline for R&M-related manpower costs to perform specific related tasks.

Apart from the case studies, other sources were examined in order to better understand the costs associated with R&M. These efforts to shed some light on probable development costs are not a panacea, but should help consolidate recent findings on the total manpower costs of R&M programs as well as providing a means of estimating the manpower portion of the task costs of R&M activities during the development phase of the system life

cycle. In some cases, manpower makes up most of the cost associated with the task element.

The intent here is not to develop a methodology for estimating the cost of reliability in a program but, instead, to use data collected by individual case studies to make inference as to the cost of selected activities that generally are accepted as contributing to improved reliability in program development. With these guidelines, managers at all levels should at least be able to make rational judgments about the manpower costs associated with specific task activities within a program. These data, added to the costs of special facilities and hardware, should provide a fair estimate of the costs associated with the tasks.

The allocation and accounting for costs in a typical program are accomplished using an established WBS, the accounting method used to collect cost by activity, and usually will not support an analysis to determine the cost of reliability activities like "Environmental Stress Screening" and R&M-related design activities. A recent study by Hall, Milliren and Schneider of the Boeing Aerospace Company identifies the manpower costs of reliability activities (see Fig. F-5) in 13 missile and space programs. Reliability program costs were presented relative to the engineering program budget measured in man-months per year (MM/YR) as shown in Fig. F-2.

Considering only the major programs, the range of engineering efforts for one year in the major program is shown for programs during the validation and FSD phases in Fig. F-3.

The authors suggest that three qualifiers should provide insight to the users for making estimates from the above table. First, system complexity directly affects the engineering program total activity--the more complex the system, the higher the cost. Secondly, the degree of concurrency in the program is a major influence; more concurrency requires higher annual engineering budgets. Finally, program size is itself an influence--generally, the higher the production, the higher the cost.

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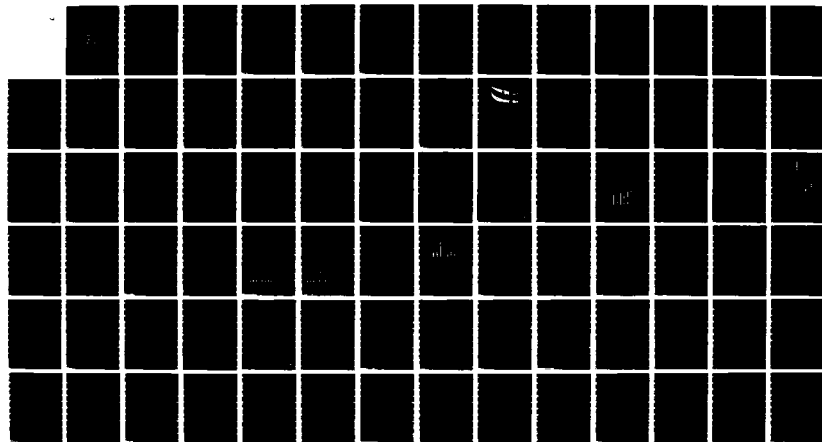
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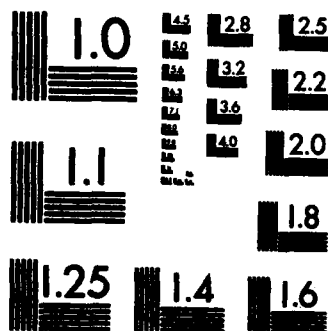
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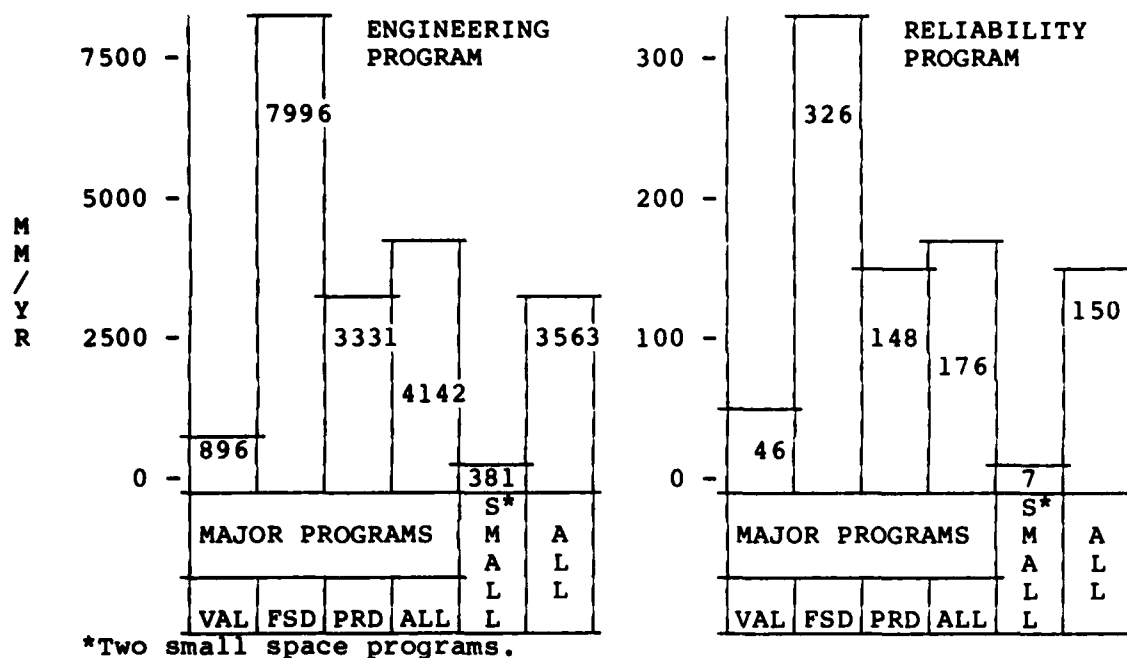


FIGURE F-2. Average Engineering and Reliability Program Task Expenditures (MM/YR)

Program Phase	Engineering Program Expenditures (MM/YR)		
	Low	Average	High
FSD	5,866	7,995	10,503

FIGURE F-3. Total Engineering Program Expenditures--Major Programs (MM/YR)

Using the average program values for both engineering and reliability program (MM/YR) expenditures, the size of the reliability program can be estimated, relative to the total engineering program. During FSD, the range of total engineering expenditures, relative to the average program was roughly  $\pm 30$  percent (see Fig. F-3).

Knowing the size of the reliability program expenditure in relation to the total engineering budget provides insight for a major portion of the cost associated with many of the reliability tasks that might be a part of a development program. These tasks are listed in Fig. F-5. A caution worth remembering is that these expenditures are for "people cost only" to some specific reliability tasks.

Reliability program expenditures ranged from a high of 427 to a low of 6.4 MM/YR for the 13 programs. The corresponding level of effort, relative to the engineering program MM/YR ranged from 1.5 percent to 13.1 percent. Figure F-4 portrays averages of these factors for the 13 programs.

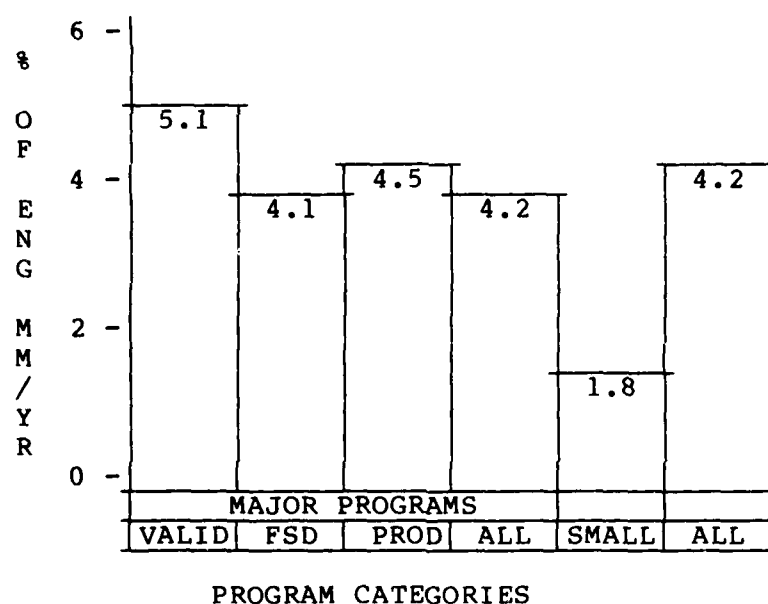


FIGURE F-4. Reliability Program Expenditures  
Percent of Engineering Budget



As can be seen from Fig. F-4, the average expenditure for R&M tasks listed in Fig. F-5 was approximately four percent. In a separate study, the Naval Sea Systems Command places the cost of the average reliability program at 4.1 percent of the total contract value for FSD. This finding was based on a study of 22 complex electronic systems built by 17 contractors. In general, they found that reliability program expenditures decreased to about 2.5 percent as the size of the program increased. This finding is similar to those documented in the Boeing study. It should be noted that in both the Navy and Boeing studies the percentage of FSD cost for R&M does not include the effort extended by designers toward R&M.

In yet another attempt to identify R&M program costs, the Air Force Acquisition Logistics Division of AFLC stated that the costs of R&M are not readily visible. Those that are visible are generally only for the R&M department and do not include the effort expended by designers toward R&M. Great care must be taken if R&M costs as a percentage of development costs are to be used as an indicator of program goodness. Examples of this are that a high percentage could indicate poor system integration of R&M while a lower percentage could indicate either good integration or an underestimation of the effort required.

Manpower cost for reliability tasks can be derived from the Boeing study mentioned previously. Costs associated with the specific tasks are shown in Fig. F-5. This further breakdown of the reliability costs by task can be useful in formulating estimates for specific activities. When the particular task is manpower-intensive, the cost may be reasonably close to these estimates. For other activities such as ESS or testing, the cost of facilities and hardware must be added to obtain a representative cost. Figure F-5 depicts manpower costs for each of the reliability WBS tasks identified plus an estimate of other Engineering Support. This other support is representative

of the tasks that design engineers provide in support of those reliability and maintainability tasks listed in Fig. F-5.

Program Task	FSD Phase
Reliability Program Plan	.1
Subcontractor Control	3.6
Program Reviews	1.7
FRACAS and FRB	10.5
Reliability Analysis	4.9
FMECA	8.4
Sneak Circuit Analysis	-
Electronic Parts/Circuit Tolerance Analysis	3.1
* Parts Program	51.0
Critical Items	.1
Effects of Test, Storage, etc.	.7
Reliability Testing	9.8
Other Engineering Support	<u>6.0</u>
Total	100.0

FIGURE F-5. Expenditures for Reliability Tasks  
Percent of Reliability Budget

\* The manpower costs associated with the parts program appears higher than on the typical electronic program. The Naval Sea Systems Command study places this value at 33 percent for the 22 programs it evaluated. The Boeing study looked at only missile and space programs where in the past there was more emphasis on the parts control program.

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## 2. Costs and Benefits of Program Maturation

Without exception, each of the case studies has identified testing as a vital part of all R&M programs. Testing identifies problems that can be solved in a variety of ways that include design changes, manufacturing changes and revised operating procedures. The idea that R&M can be improved through an overall program of testing, designed to mature the hardware, is at issue here. Even though case studies did not identify an overall "maturation program," the testing that was conducted did produce maturing results in varying degrees. The vital elements of any maturation program can be reduced to orderly testing of the hardware, analyzing the failures that are identified, incorporating fixes and then measuring results. The tests used to perform this function vary from program to program, but in the final analysis each of our case study programs has tested the hardware, analyzed the failures, and taken appropriate corrective action, and a more reliable product resulted.

Testing, like other activities within a development program, costs money. Program managers are constantly faced with budgetary constraints that force them to tailor their development programs. The intent is to quantify the costs and benefits associated with several testing programs and to provide substantiation for including maturation testing in a program structure because of the high return that it offers.

In the case of the APG-66 radar the benefit-to-cost ratio for maturation tests performed was approximately 20:1. Additionally, payback periods are quite short, occurring at the 230,000 flying-hour point, a milestone the F-16 passed in April 1983. There also are substantial reasons to believe that benefits achieved to date are conservative estimates that can be improved still further, given adequate incentives.

a. Cost Benefit of the APG-66 Maturation Test Program

At the outset, it is important to understand that the APG-66 did not have a "Maturation Test Program," per se. This analysis evaluates the combined effects of several discrete tests and uses the output to obtain results that demonstrate an improved reliability. For this analysis, this maturation test program included both growth and qualification testing.

Testing began in mid-1977 with the FSD growth test and for purposes of this analysis, was completed with the Production Reliability Qualification test in late 1980. It is likely that the full benefit of all corrective actions taken as a result of those tests has not yet been fully realized. An additional 420 hours of testing was conducted subsequent to these tests and 47 corrective actions were taken to correct identified failures.

For this analysis, however, benefits stemming from corrective actions must have been achieved and measured in the field during a period of time roughly equivalent to the calendar time for maturity testing. For example, the total calendar time for the maturity testing covered approximately 42 months. During these 42 months, over 2800 test hours were accumulated on the radar, failure modes were identified and corrective actions taken. Specific tests and test hours are shown in Fig. F-6.

The benefits that accrued as a result of these tests have been measured over a calendar period approximately equal to the test period after the equipment reached the field. Field reliability values are as reported by the Air Force Maintenance Data Collection System (AFM 66-1) and are shown in Fig. F-7. Note the 4:1 improvement in reliability over the period. Mean Time Between Maintenance (MTBM) Type 1, is the surrogate used for operational reliability.

Costs associated with the maturity testing have been calculated. These expenditures represent less than 10% of the total costs of the APG-66 development contract and will result in a significant cost avoidance over the life of the system.

<u>Test Type</u>	<u>Test Hours</u>
FSD Growth	420
FSD Pre RQT	470
FSD RQT	730
Prod. Growth	230
Prod. RQT	<u>956</u>
Total	2806

FIGURE F-6. APG-66 Maturity Test Hours

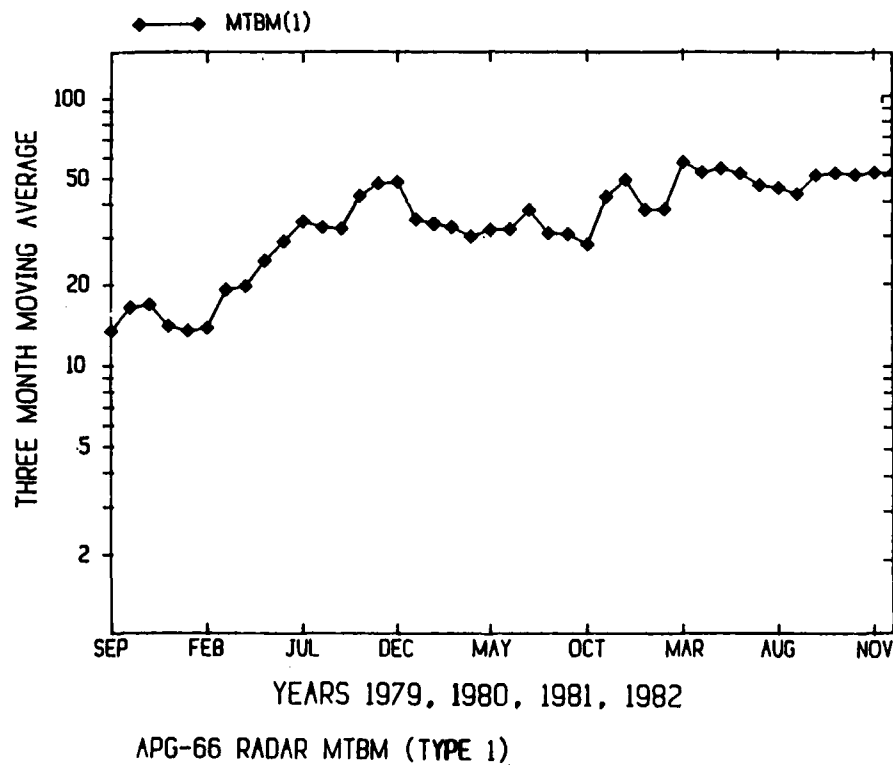


FIGURE F-7. Reliability Growth

Costs for maturity testing are presented in Fig. F-8. These costs do not include the baseline manpower related costs of reliability presented in Section A-1 previously.

Total Test Hours	2806	
Cost per test hour	\$700	
Subtotal		\$2.0M
Test Asset Cost	.6M	
Number of test assets	3	
Subtotal		\$1.8M
Total Maturity Test Cost		\$3.8M

FIGURE F-8. APG-66 Radar Maturity Test Costs

Return on investment (ROI) for the maturity testing activity and the payback period are indicators of the value of activity. ROI is conservatively 20:1. This value can be demonstrated using the field reported MTBM (TYPE 1) for the 3<sup>rd</sup> quarter 1979 (14 hours), the 4<sup>th</sup> quarter 1982 (52 hours) and the Operating and Support (O&S) cost avoidance from Fig. F-9.

This cost avoidance is a result of all the factors that influence change in MTBM TYPE 1. These factors include the results of maturity testing, RIW contract, the improved training of personnel that results from having the equipment to work on, maturing of the logistics activities that support the system and an improved pilot understanding of how the system works. Maturity testing, a major contributor to this change is estimated to account for

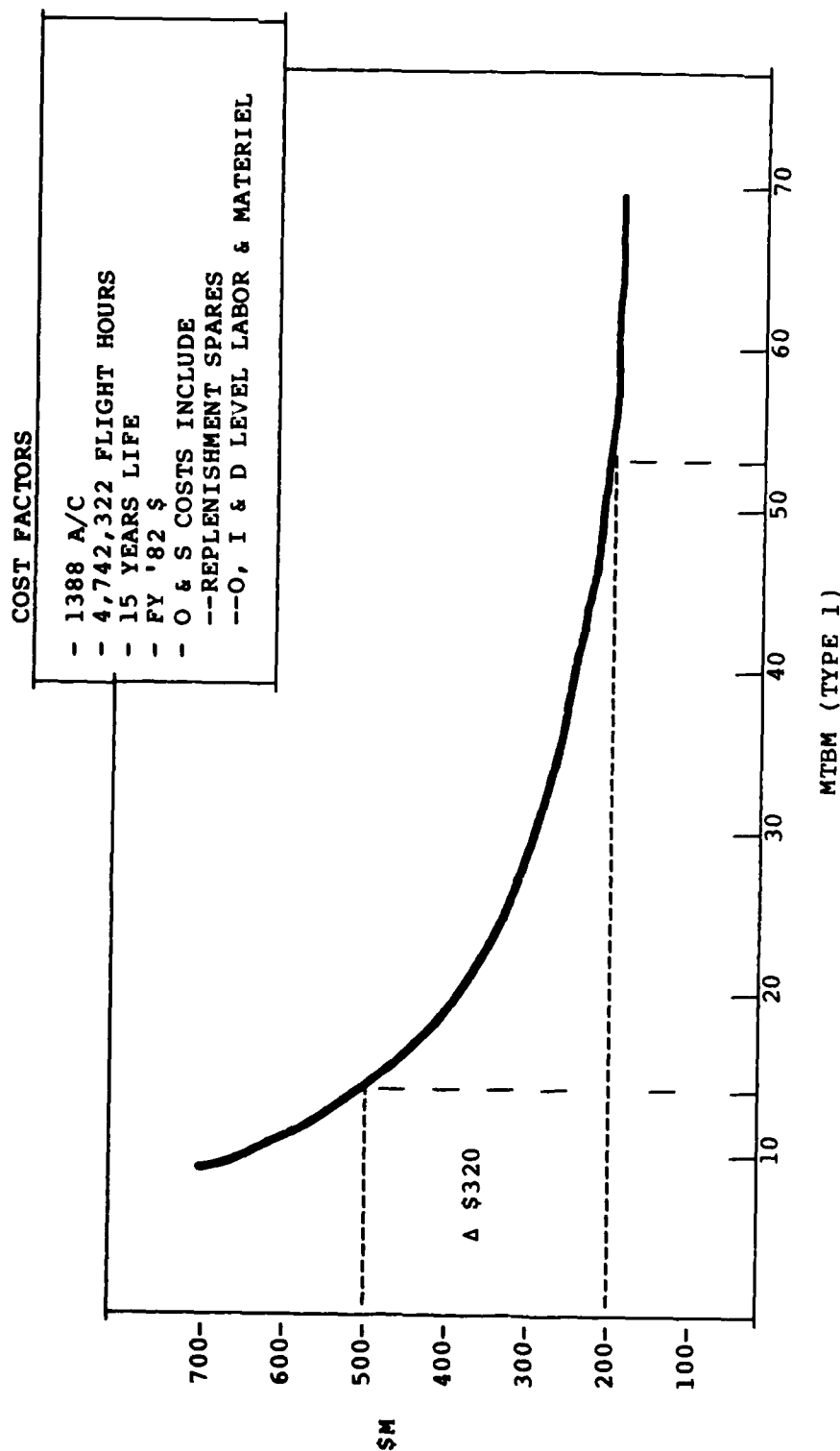


FIGURE F-9. APG-66 Operating & Support Cost Avoidance

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25 percent of the reported improvement in field reliability. In the case of the APG-66, this represents a cost avoidance of \$80M, (20:1 ROI). Converting this cost avoidance to flying hours has the effect of reducing the dollar cost per flying hour by \$17, based on the flying hours shown in Fig. F-9. From this perspective, the payback period is 230K flying hours, a point that the F-16 A/B passed in April 1983 as shown in Fig. F-10.

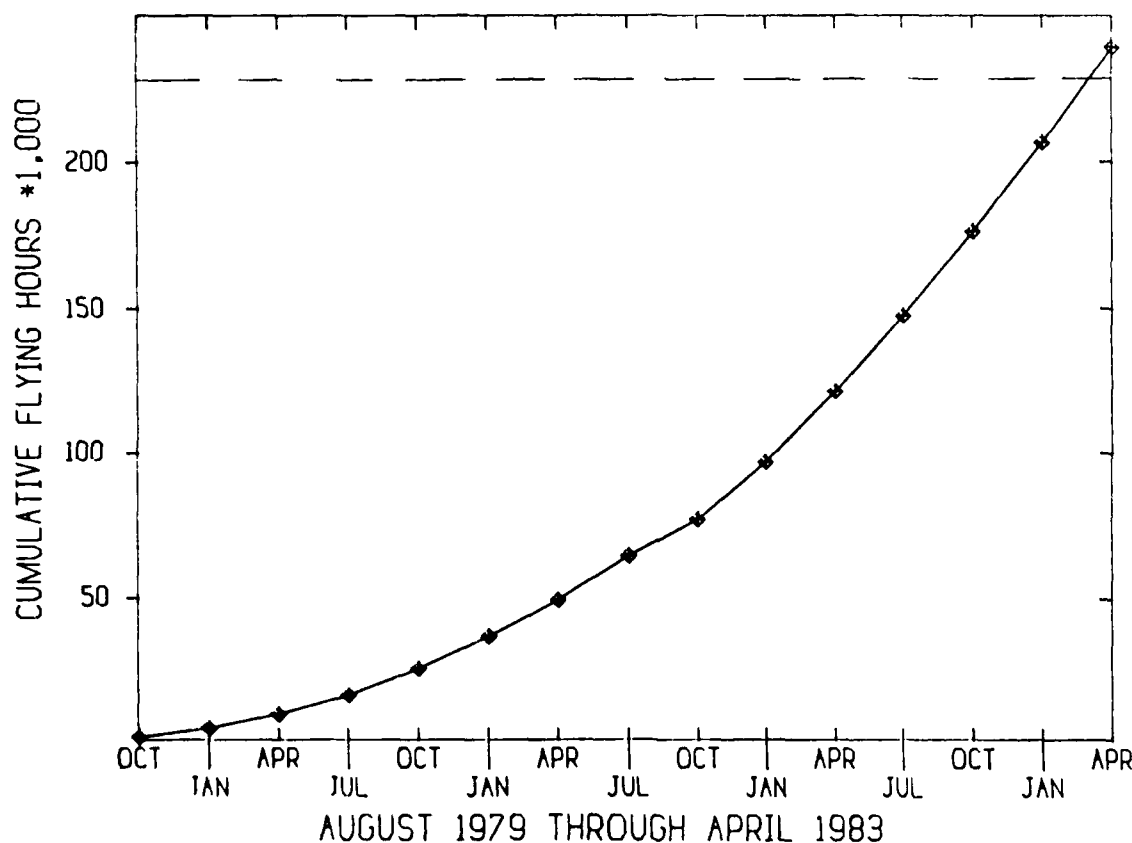


FIGURE F-10. F-16 A/B Total Flying Hours



b. Cost Benefit of the TPQ-37 Reliability Improvement Program

The TPQ-37 offers another good example of how reliability improvements provided for improved readiness of fielded hardware with a return on investment (ROI) estimated to be 15:1. In this case, the TPQ-37 was somewhat unique in that it progressed from Advanced Development (AD) into production without a full scale development phase. Early in the production phase, the Army funded an ECP as a part of a reliability improvement program (RIP) aimed at improving the field reliability.

The RIP was funded at \$5.5 million. Improvements in reliability during the period are shown in Fig. F-11. This improvement from 33 hours MTBF to more than 120 hours results in a cost savings of more than \$80 million, based on reduced repair cost for the system relative to currently-reported system failure rates. The savings was calculated using a nominal cost of \$5000 per field repair action. The number of failure events during the estimated 20-year life of the TPQ-37 was reduced by over 16,000 as a result of the improved reliability.

The payback period for the RIP is also quite short. Even with the relatively slow production rate, the payback for the total \$5.5 million contract is estimated to occur in 1985.

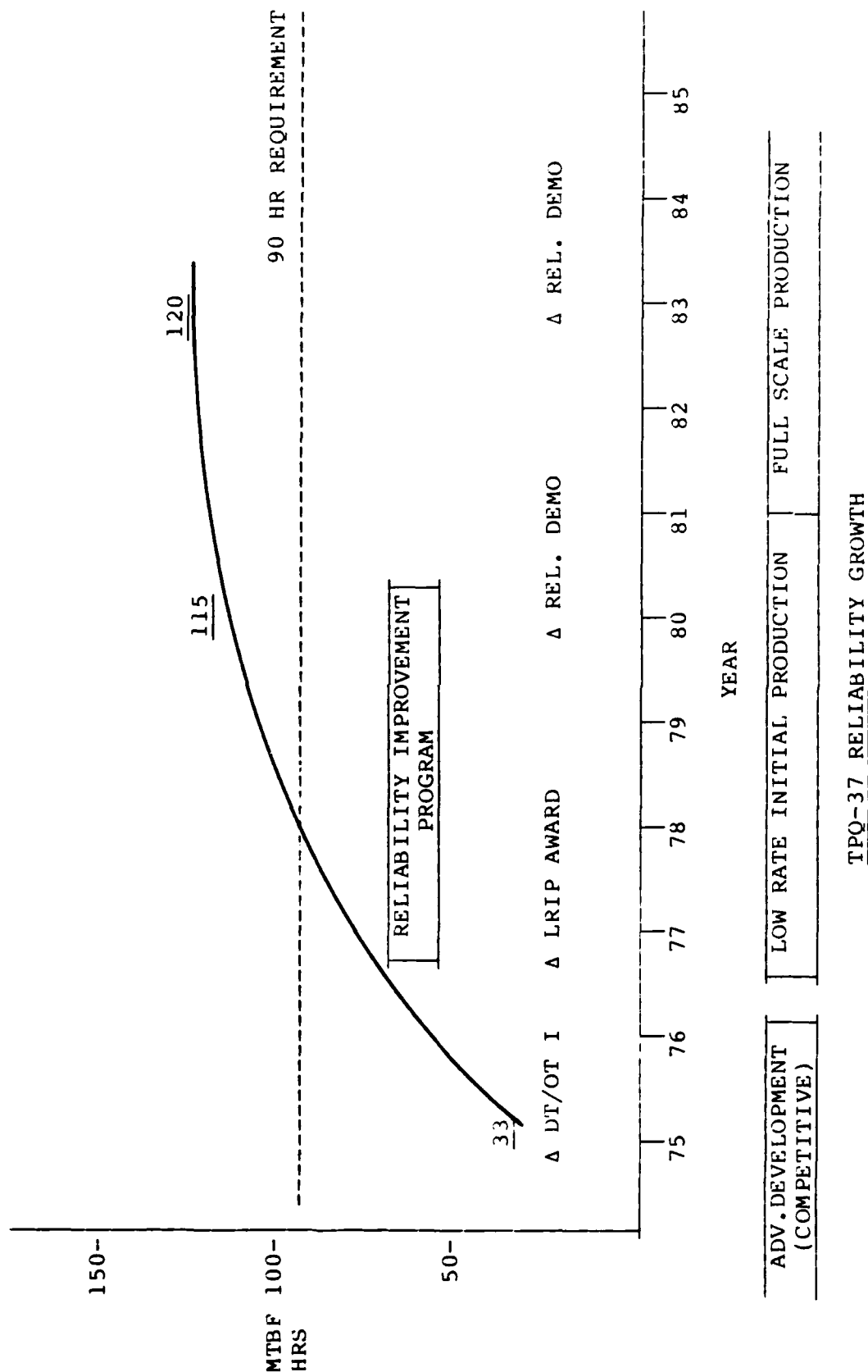


FIGURE F-11. FIREFINDER TPQ-37 Reliability Growth

### 3. Cost Aspects of Environmental Stress Screening

One definition of ESS is "the application of a specific combination of environmental stresses on an accelerated basis, but within design capability, in an attempt to surface latent or incipient flaws which in all likelihood would show up in the operational environment" (ESS of Electronic Hardware: "To Know It Is to Love It", Neil Mandel). Several methods have been used over the past few years in an effort to improve the ESS process. To date, evidence suggests that the specific environments and durations must be tailored to the hardware to be screened in order to be effective, and there is no universally accepted ESS technique that can be applied to all types of parts and equipments. Generally, however, it is agreed that varying amounts of random vibration and thermal cycling do precipitate flaws that might show up later in the operational environment. Removing these flaws early in the manufacturing process translates to lower production costs and improved operational reliability and maintainability performance. It is important to note, however, that removing flaws is not enough. A systematic appraisal of why the part failed and the correction necessary to preclude its recurrence is mandatory for optimum results.

The cost benefits associated with screening bad parts at the lowest level in the manufacturing process can be quantified. One study has shown that defective ICs will cost \$75 to correct at the subassembly level and as much as \$200 at the assembly level. Part failures corrected at the system level may cost in excess of \$1000 and once in the field will probably cost over \$2000. To be economically prudent, the cost of screening should be less than the cost of repair during in-house testing of the hardware prior to shipment to the customer with the by-product of improved operational performance. Some companies may find the capital expenditure for equipment to perform the necessary screens

to be excessive. Estimates vary, but costs to implement 100 percent testing of components at three temperature levels could cost in excess of \$3M for the capital equipment (Ref. Nov. 16, 1982, R&M Core Group Briefing by J. L. Capitano)

Another source of information from a manufacturer of screening facilities (Screening Systems, Inc., El Toro, CA) indicates that a combined environments (temperature cycling and tri-axial quasi-random vibration) chamber with a 30"-diameter head and 450-pound capacity can be purchased for about \$100K. These chambers are currently in use on the Navy MK-48 Torpedo program. Additional information on the facilities cost aspects of combined environments test facilities is contained in "Mission Profile Test Costs, Facilities and Test Performance," AFWAL TR 80-3087, September 1980, published by the Air Force Flight Dynamics Laboratory, WPAFB, OH.

The marginal cost of performing ESS at the subassembly and system level is \$20 and \$40, respectively, based on one experience at Gould for a 5000-part system. Considering the range of airborne radars from the case studies, 9500 parts for the APG-66 and 18,830 parts for the APG-63, and assuming 100 parts per subassembly, one might infer that the cost of screening an airborne radar would be from \$1900 to \$3800 for all subassemblies and from \$760 to \$1500 each at the system level. The total cost for ESS of each system would range from about \$2660 to \$5300. A reference set of stress screening cost models is included in the Institute of Environmental Sciences' publication titled "Environmental Stress Screening Guidelines."

The benefits that accompany these costs could prove to be the most important aspect of the relationship. Results of ESS (random vibration) by IBM on the F-15 Central Digital Computer indicate significant increase in the failure rate of the 50 computers screened, which led to a 6-to-1 reduction in infant mortality observed during prime integration test. In a separate test on the F-15 radar subsystem, a six-day reduction in the manufacturing schedule

was realized through ESS. As a result, Hughes Aircraft reduced the cost of each radar to the Air Force by \$800.

The evidence seems clear. Environmental stress screening, properly administered, can help ensure hardware performance and reduce the cost of rework while minimizing schedule delays that accompany the rework and, most importantly, reduce manufacturing defects in delivered hardware. The resultant improved reliability will reduce system operating and support cost throughout its useful life, while at the same time also improving the operational readiness of the system.

#### 4. Depot Repair Cost Savings for the ARN-84

Gould NavCom System division reported their experience using Environmental Stress Screening on the ARN-84 TACAN. Their ESS emphasized the use of thermal shock to precipitate failures at the piece-part level. Prior to implementation of this process, the Navy was reportedly experiencing approximately 200 equipment operating hours mean time between failure with the ARN-84. After implementing this process, the Navy is reportedly experiencing approximately 2000 equipment operation hours mean time between failure. Based on these two MTBF values, the cost savings for only the depot level repair for the ARN-84 was calculated to be in excess of \$5 million per year for the 5000 sets currently in use by the Navy. The cost of depot level repair is shown in Fig. F-12 below for these two MTBF values.

	200 O/H MTBF	2000 O/H MTBF
Flying Hours per year	300	300
K factor	1.5	1.5
Operating Hours Per Year Per Set	450	450
Failures Per Year Per Set	2.25	.225
Cost of Repair	\$500	\$500
Depot Level Repair Cost Per Set Per Year	1125	112.50
Total Depot Level Repair (5000 Sets)	5,625,000	\$562,500

Year Cost Savings

\$5,062,500

FIGURE F-12. Depot Level Repair Costs

The savings in depot repair costs per set per year are approximately 6% of the acquisition cost of the equipment. Cost savings for other repair cost assumptions are shown in Fig. F-13, based on 450 and 900 operating hours MTBF.

It should be recognized that this savings does not include any reduction in field level maintenance or for spares. Including these factors could substantially increase the calculated savings and reduce the payback period. Additionally, Gould reported that this result was achieved at no increase in unit price to the Navy. The costs incurred to screen the parts were offset by the savings from less rework during manufacturing.

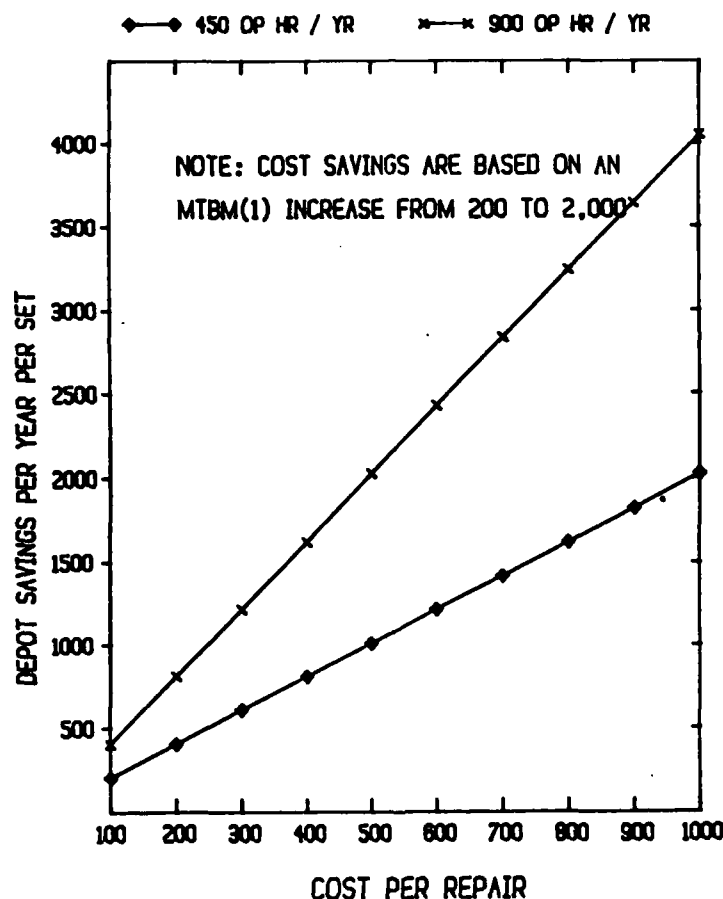


FIGURE F-13. ARN-84 Depot Cost Savings

## 5. Part Costs Considerations for Weapon Systems

The costs of parts used in electronic systems represent a substantial part of the total costs for the system. Historically, standards have been developed to ensure that the desired or required quality part was available and used for military systems. MIL-HDBK-217D describes in detail the quality level and quality factors associated with various classes of parts. Claims are made from time to time that commercial parts could be used in military applications to achieve the same results if they were screened properly. While this thought is intuitively appealing, we have no data to support the claim. In fact, based on failure rate data for the wide variety of parts found in MIL-HDBK-217D, quite the opposite may be true.

No attempt has been made here to address the claim that commercial parts can do the same job as MIL-STD parts if screened properly as we believe this is a separate issue. Our analysis looks at the total cost implications of parts given the failure rates that have been observed and are documented in MIL-HDBK-217D. Microelectronic devices were selected for this analysis and the failure rates associated with varying part quality levels are shown in Fig F-14.

Microelectronic devices were selected for this analysis for several reasons. First, the radar systems case studies document that 35-40 percent of the electronic parts are micro-circuits. Secondly, the devices have very low failure rates and it was felt that any conclusions reached based on these low failure rate devices could be extrapolated to the other higher failure rate components that make up the electronic systems.

Our analysis is based on the following key assumptions:

(1) Three different part failure rates are used. These rates are extracted from MIL-HDBK-217D. MIL-M 38510 parts, quality level B have a failure rate of 1.0. Quality level B-1 and B-2 have failure rates of 3.0 and 6.5, respectively.

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Quality Level	Description	IQ
S	Procured in full accordance with MIL-M-38510, Class S requirements.	0.5
B	Procured in full accordance with MIL-M-38510, Class B requirements.	1.0
B-0	Procured in full accordance with MIL-M-38510, Class B requirements except that device is not listed on Qualified Products List (QPL). The device shall be tested to all the electrical requirements (parameters, conditions and limits) of the applicable MIL-M-38510 slash sheet. No waivers are allowed except current and valid generic data may be substituted for Groups C and D.	2.0
B-1	Procured to all the screening requirements of MIL-STD-883, Method 5004, Class B and in accordance with electrical requirements of MIL-M-38510, DESC drawings, or vendor/contractor electrical parameters. The device shall be tested to all the quality conformance requirements of MIL-STD-883, Method 5005, Class B. No waivers are allowed except current and valid generic data may be substituted for Groups C and D. This category applies to DESC drawings and contractor prepared specification control drawings (SCD's) containing the above B-1 screening and quality conformance requirements.	3.0
B-2	Procured to vendor's equivalent of the screening requirements of MIL-STD-883, Method 5004, Class B, and in accordance with the vendor's electrical parameters and vendor's equivalent quality conformance requirements of MIL-STD-883, Method 5005, Class B. Applies to contractor prepared SCD's containing the above B-2 screening and quality conformance requirements.	6.5
C	Procured in full accordance with MIL-M-38510, Class C requirements.	8.0
C-1	Procured to screening requirements of MIL-STD-883, Method 5004, Class C and the qualification requirements of Method 5005, Class C. Generic data may be substituted for Groups C&O.	13.0

FIGURE F-14. IQ Quality Factors

(Table 5.1.2.5-1. MIL-HDBK-217D Microelectronic Devices)

(2) Microcircuit costs range from \$1 to \$130. On average, costs per part are in the range of \$6-7.

(3) As a class, microcircuits have a failure rate of 1.5 per million part operating hours.

(4) MIL-M 38510 parts cost twice as much as vendor equivalent parts screened to MIL-STD 883 requirements.

(5) The cost to repair is dependent on how soon the failure is identified. These costs are shown in Fig F-15.

(6) Systems contain 5000 microcircuits.

<u>LEVEL</u>	<u>COST PER FAILURE</u>
PART	1.00
SUBASSEMBLY	75.00
ASSEMBLY	200.00
SYSTEM	1000.00
FIELD	2000.00+

FIGURE F-15. Repair Cost Per Failure

A number of excursions were made to determine the part preference break-even point. Details of those excursions are contained in Appendix C. Figure F-16 shows the resultant part preference based on an average cost per part of \$7. Even though higher average part costs tend to move the curve to the right, the overall conclusions do not change until the average part cost reaches approximately \$100.

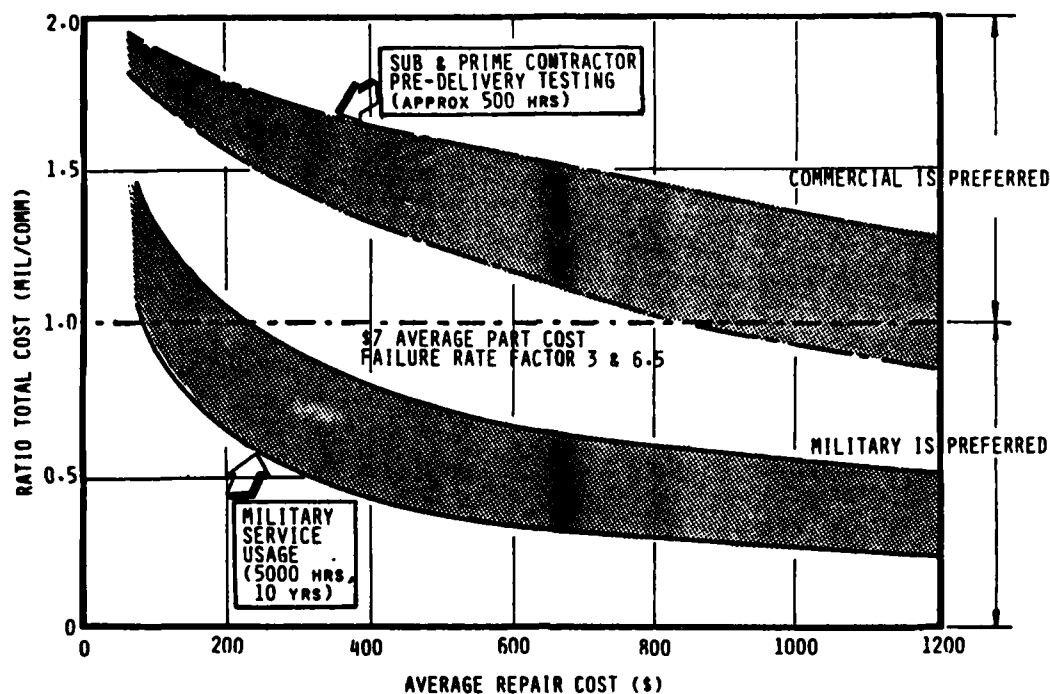


FIGURE F-16. Microcircuit Resultant Part Preference

Figure F-16 depicts two bands of data that reflect slightly different conclusions. The bands are a result of plotting the total costs of MIL-M 38510 parts divided by the total costs of vendor equivalent parts (commercial) at various average repair costs for the two failure rates listed. The upper curve of each band is for a failure rate three times higher than demonstrated for the MIL-M 38510 part and the lower curve is for 6.5 higher. The center (dotted) line represents the break-even point for each combination considered.

One additional factor has been used to complete the analysis as shown. Notice that the upper band is based on an equipment usage of 500 hours and the bottom band 5000. These operating hours were selected to represent the number of part operating hours that a typical equipment might see in the factory during

the manufacturing process and subsequently in field use. For example, a system with 5000 microcircuits would expect to see approximately four part failures during the first 500 hours of operation when MIL-M 38510 microcircuits were used. During the same period, a vendor equivalent part, quality level B-2 would expect to see approximately 25 failures during the same period.

Based on this analysis, parts with low failure rates as demonstrated by the MIL-M 38510 parts are preferred to parts that have exhibited higher failure rates when the costs of repair is high even though the operating hours might be low. When operating hours are high, as might be expected with most equipment delivered to the military, the lower failure rate part is preferred at virtually all expected repair cost levels. Figure F-17 depicts these part preference choices.

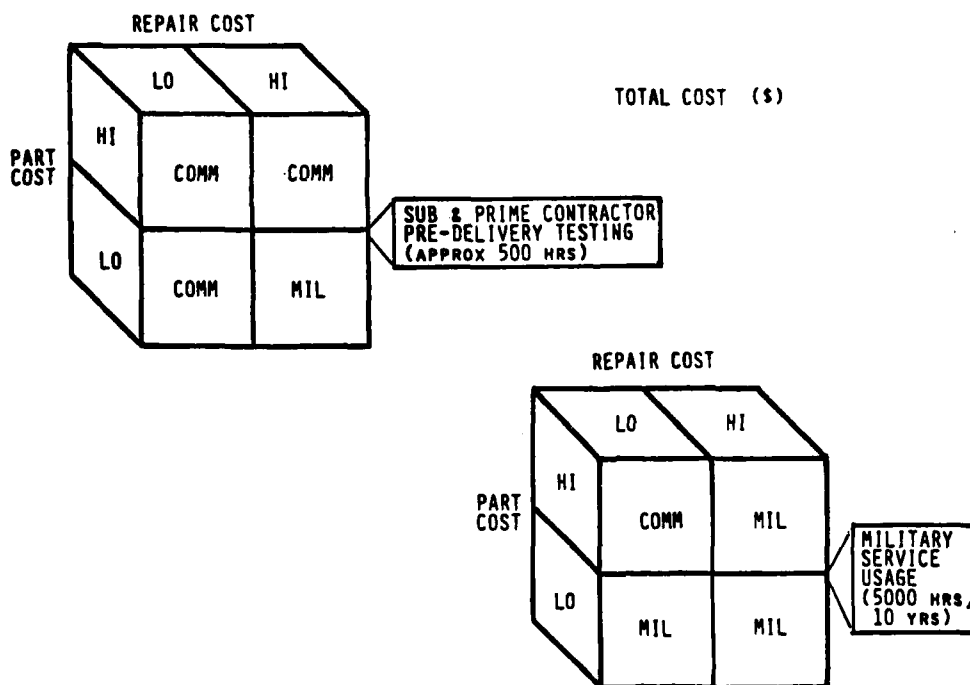


FIGURE F-17. Part Preference Choices

This analysis does not answer all the questions one might ask concerning the cost and benefits of military versus commercial parts. It does, however, point out that if commercial parts can do the job required of the equivalent military part, they must be prepared to demonstrate failure rates that approach those of the MIL-M 38510 parts if they are to be cost-effective from the military point of view even though their acquisition costs might be considerably less.

## 6. The High Cost of CNDs

Throughout the case studies, problems caused by inadequate diagnostics are legion. The diagnostics problem is discussed in the main report and in Appendix E. This section quantifies the costs associated with CNDs, (cannot duplicate or no defect maintenance events) and provides the incentive to accelerate diagnostics improvements.

For example, during the period 1980-1982, approximately 70 percent of all corrective maintenance events on the F-15 and F-16 radar systems were for CND actions. During the same period, between 30 and 50 percent of all corrective maintenance man-hours were consumed in response to CND's. These percentages are shown in Fig. F-18 for the APG-63 and in Fig. F-19 for the APG-66.

Another important measure of the effect of CNDs on the maintenance function can be seen in Figs. F-20 and Fig. F-21 for the APG-63 and APG-66, respectively. For the period, the rate of CND events per flying hour for the radar alone averaged .10 for the APG-63 and .07 for the APG-66. Rate trends are apparent in the figures as presented.

The actual costs attributable to each CND have been calculated and are presented in Fig. F-22. Costs were calculated based on data from the AFLC K051, D056B and D056T analysis products. The average cost per MMH is based on a known 1980 labor rate of \$35 per maintenance man-hour for logistics support cost computation contained in the K051 report. The average cost of \$30.87 and \$12.20 per CND per flight hour for the APG-63 and the APG-66 are conservative, given the inaccuracies of the reporting systems, but still point out the magnitude of costs that can be avoided by improving the diagnostic capabilities of the radar systems.

# F-15 A/B & C/D APG-63 RADAR

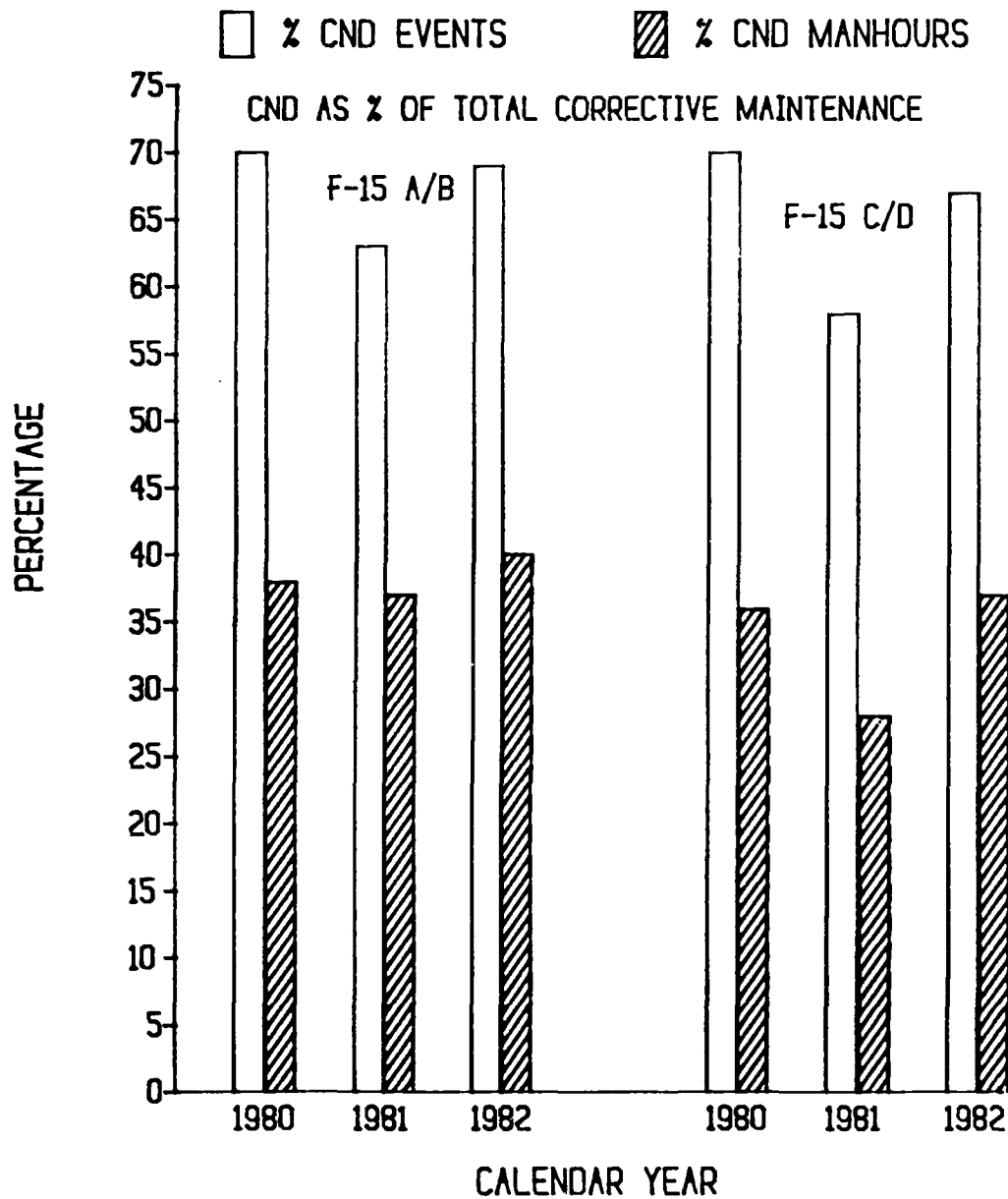


FIGURE F-18. APG-63 Maintenance Events Summary

# APG-66 RADAR

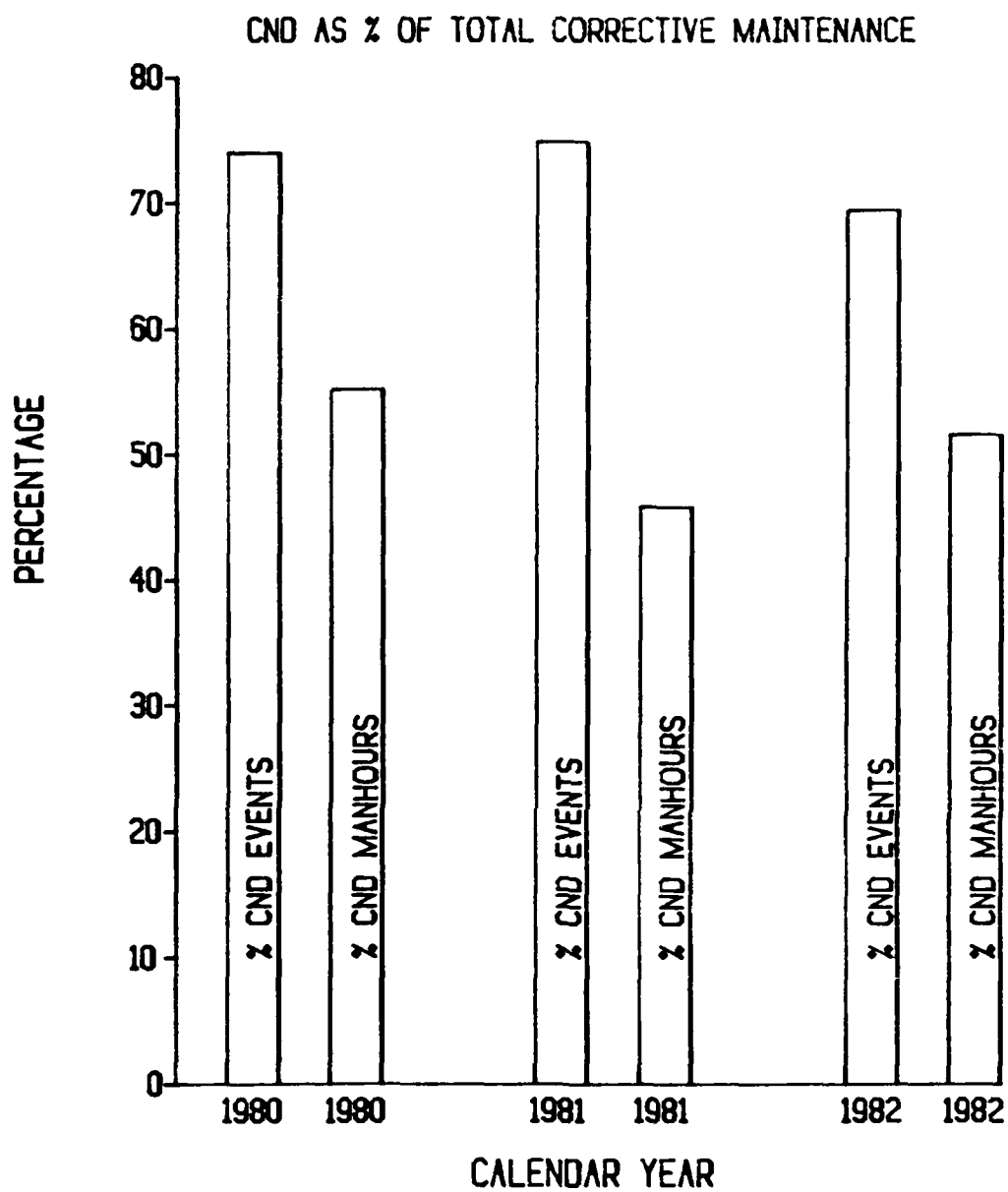


FIGURE F-19. APG-66 Maintenance Events Summary



# F-15 A/B & C/D APG-63 RADAR

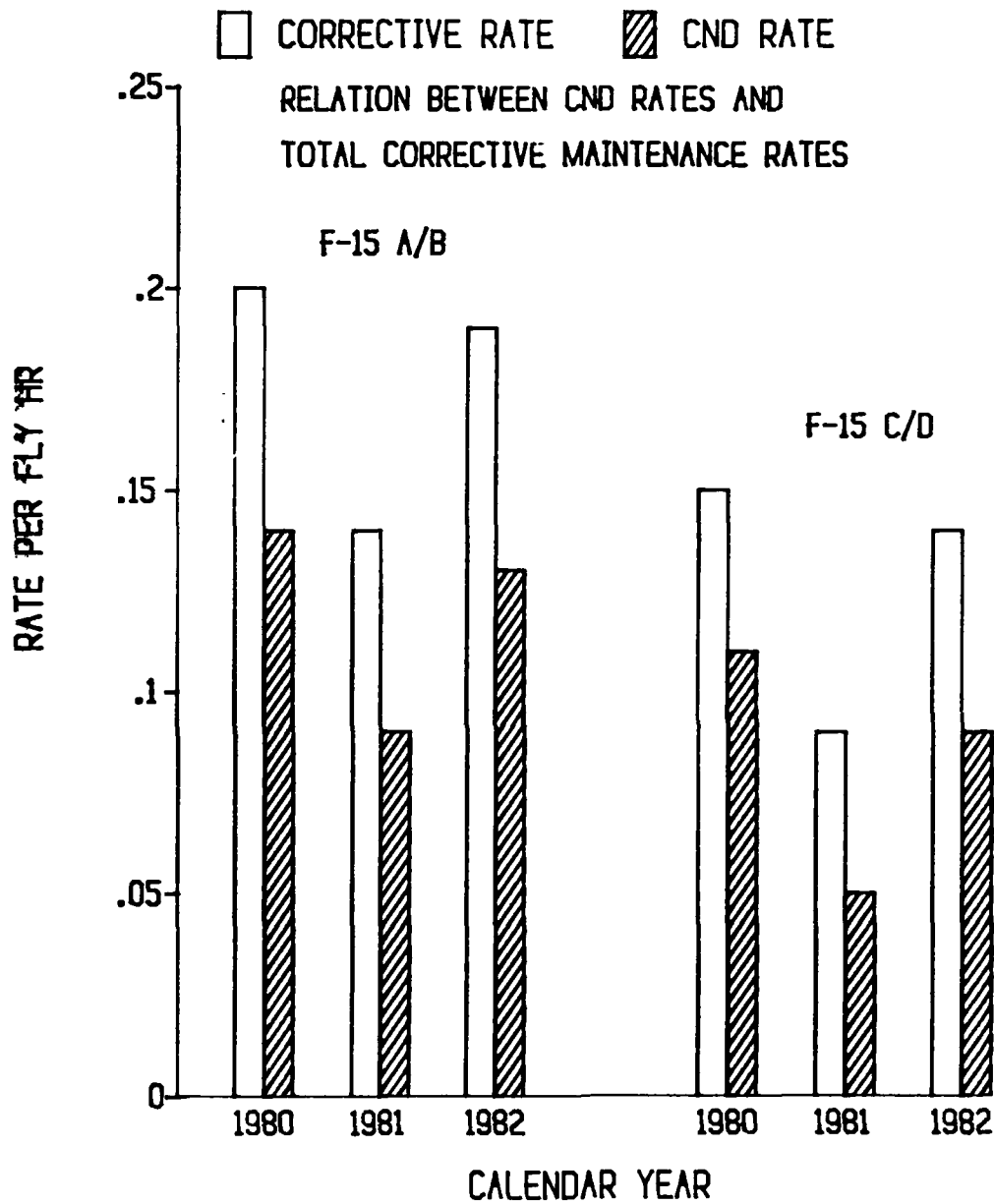


FIGURE F-20. APG-63 Maintenance Events Rates

## APG-66 RADAR

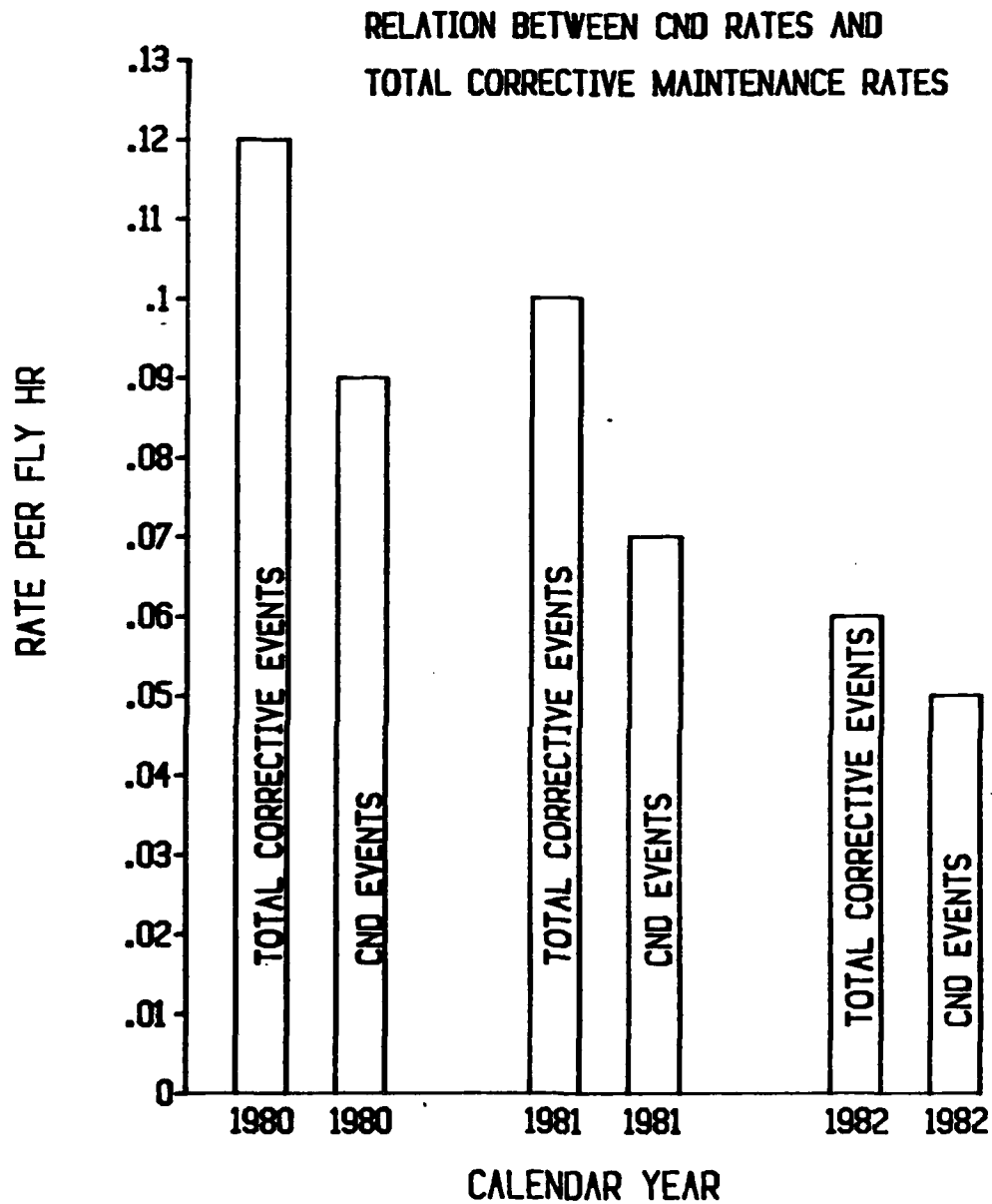


FIGURE F-21. APG-66 Maintenance Events Rates

<u>AN/APG-63 RADAR</u>	<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>THREE YR AVERAGE</u>
TOTAL CORRECTIVE EVENTS	20,220	15,767	23,609	19,865
TOTAL CND EVENTS	14,113	9,723	16,183	13,340
TOTAL FLIGHT HOURS	108,517	127,093	143,550	126,387
CND EVENTS PER FLIGHT HOUR	.130	.077	.113	.106
MMH PER CORRECTIVE EVENT	12.71	16.00	15.26	12.71
MMH PER CND EVENT	6.72	8.39	8.61	7.91
CND MMH PER FLIGHT HOUR	.873	.642	.971	.834
AVG COST PER MMH	35	37	39	37
CND COST PER FLIGHT HOUR	30.57	23.75	37.86	30.87
YEARLY CND COST	3.3M	3.0M	5.4M	3.9M

<u>AN/APG-66 RADAR</u>	<u>1980</u>	<u>1981</u>	<u>1982</u>	<u>THREE YR AVERAGE</u>
TOTAL CORRECTIVE EVENTS	3,431	5,655	6,466	5,184
TOTAL CND EVENTS	2,536	4,231	4,926	3,898
TOTAL FLIGHT HOURS	29,244	56,571	106,955	64,257
CND EVENTS PER FLIGHT HOUR	.087	.075	.046	.061
MMH PER CORRECTIVE EVENT	5.68	8.55	9.33	7.85
MMH PER CND EVENT	4.25	5.89	6.16	5.43
CND MMH PER FLIGHT HOUR	.369	.441	.284	.330
AVG COST PER MMH	35	37	39	37
CND COST PER FLIGHT HOUR	12.90	16.30	11.06	12.20
YEARLY CND COST	.38M	.92M	1.18M	.78M

FIGURE F-22. Radar CND Costs (\$)

## B. TEST ASSETS

The determination of the need and commitment of assets required for a properly executed reliability and maintainability program is critical to the success of a program. Due to budget restraints there is a tendency to minimize the expenditure for test assets in almost all development programs. This results in a high likelihood of there being too few assets to accomplish program critical testing. A scarcity of test assets often causes management to place a lower level of priority on reliability and maintainability testing than on other test activities. For these reasons it is important that adequate assets be planned for R&M activities. If reallocations or reassignment of the R&M test assets are considered, the impact on R&M should be assessed.

In a well-planned integrated test program, R&M data should be obtained from the performance evaluation and environmental qualification tests to be used as soon as possible in an R&M growth test program.

The economics of effective R&M development are dependent on early testing and early corrective action. The cost for corrective action increases rapidly as program time passes and it may not be cost-effective to incorporate changes as production advances.

### 1. Assets for Reliability Testing

Assets are required for reliability development testing and reliability qualification tests, to assure that the design activities have in fact addressed the stress and environments that are expected in operation.

#### a. Reliability Development Test

Reliability development tests are needed to identify failure modes not detected by analysis. Development testing is intended to find failure modes and to provide information on ways to develop

a corrective action for these failure modes. The assets for the reliability development tests need to be available early in the development cycle, and should therefore be allocated the first units available. This allows the gathering of early failure data and incorporation of corrective actions prior to or near the beginning of production. Since the configuration of the early units is not fully representative of the final design, reliability data and test hours should be attained on test articles which are dedicated to other activities. The F/A-18 APG-65 development test program used the approach of combining hours from early configuration units and added later configurations as the test progressed.

From the standpoint of gathering hours or experience on various test units, the real measure of test assets needed for reliability development tests is in terms of test hours and calendar time required to obtain these test hours, because of the impact and time sensitivity of the information that these tests produce. Efficiency is gained if multiple units are used at any one time rather than a single test unit. The minimum requirement then is for two test assets to be assigned by specific serial number to reliability development test and change them as later configurations become available.

#### b. Demonstration Tests

The tests provide a means of determining contract compliance and provide essential engineering data. The orientation and focus should be directed toward action that results in improvement in the reliability of the system as well as demonstration of compliance with specific reliability levels.

The general inclination is to pursue the allocation of test assets in first priority for demonstration testing. Demonstration testing has the potential to field valuable development data if the priority of test success is not pushed to exclusion of other data. Allocation of assets for both reliability development and

demonstration testing is in fact essential for a successful program. To provide an adequate statistical basis it is important that the demonstration be conducted on no less than two test units.

Test articles should be dedicated for use during the reliability demonstration test time period and may have other applications after the test. Reliability development and demonstration tests should be conducted as early in FSD as hardware schedules allow, with development tests conducted prior to demonstration tests.

Since changes can occur within the production process, to assure that the quality of the hardware is maintained throughout the production cycle, reliability demonstration tests on subsequent production systems should be considered. Periodic production reliability tests have been conducted on the F-15 and F-16 radars and have identified problems that were corrected.

## 2. Assets for Maintainability Testing

Test assets are needed for a program to develop and mature the BIT system. In addition, principal needs include the validation of built-in test (BIT) and maintainability demonstrations.

### a. BIT Development/Maturation

Fault insertion approaches have been shown to be of value if the fault lists are realistic and comprehensive. The assignment of a single test asset may be adequate if the asset is representative of the BIT design and has the supporting software of the appropriate configuration. Experience has indicated that it is almost impossible to design an effective BIT system from theoretical data or speculation of fault patterns. A good BIT system must be developed and matured by the individual pursuit of fault experience and diagnostic process. For this necessary process to take place it is absolutely necessary to provide a test asset system near a location where failures are generated--this test system being available to those who are continuing to grow and improve the BIT system.

The basis for BIT maturation is properly the number of faults that are experienced rather than the number of test operating hours or the number of calendar days. The efficiency of the maturation program depends upon the realism of the fault list and the efficiency of the engineering actions that are taken as a result of the information that is obtained. Data should also be obtained from the other tests and used in maturing the BIT system.

b. Maintainability Demonstration

The maintainability demonstration test, as now structured, requires a relatively short time to perform and the asset availability is normally not a problem if the value of the test has been understood by management. A single properly-configured test asset is usually adequate for the maintainability demonstration.

APPENDIX G

INFORMATION SYSTEM OBSERVATIONS



## APPENDIX G

### INFORMATION SYSTEM OBSERVATIONS

Throughout the course of this study, the number of times that the requirements for "good data" presented itself is legion. Beginning with earliest design activity and continuing throughout the service life of the equipment, good decisions can be seen to stem from good data inputs. In this appendix, we examine several events where "official data" were used to tell a story or depict an event when, in fact, a different story might have been apparent if a more in depth effort was made to understand what the data were reporting. The overall message from this portrayal is to suggest to the reader that data must always be questioned for hidden meanings. In addition, we point out existing features of service data collection systems and evaluate those systems in light of future requirements.

Wide variations in results, using data obtained from the same data base, have been observed in the course of this study. Six examples are provided as follows:

#### A. VARIATIONS IN THE USE OF DATA

##### 1. Impact of the F-16 Fleet Electrical Modification

In August of 1981, the F-16 fleet was down for a modification of the electrical system. The number of flying hours for August was 25 percent of that flown in July (1,344 versus 5,835) and recovered to only 81 percent in September (4,734 versus 5,835). The impact of the modification is clearly displayed in Fig. G-1, where all three measures show large dips. Figure G-2 contains

five bar graphs of the 1981 data, bracketed on each side by the prior year (1980) and the following year (1982). The first 1981 bar presents the entire year's data, the second 1981 bar removes the third quarter's data, the third 1981 bar is the third quarter by itself, the fourth 1981 bar removes the August data and the fifth 1981 bar is the fourth quarter data only. Figure G-3 shows the impact of the fleet electrical modification on reliability growth plots. Note that once the August data are removed, the growth line is nearly straight.

## 2. F-15 and F-16 Radar Removal Data

Many avionics experts depend on LRU removal rates as the key measure of system "goodness." The supporting rationale for use of the removal rates is quite convincing, i.e., removal rates (less removals for access and cannibalizations) are much more indicative of the total health of the system. They also include the impact of diagnostic problems, which in turn affect skill and training requirements. Inherent reliability, on the other hand, is not indicative of the total maintenance burden and, in fact, is not intended to do so as it does not include the impact of faulty diagnostics, etc. Total maintenance actions, as a measure, is much closer to removal rates in its ability to measure the total maintenance burden as it includes the impact of diagnostics, cannibalization, remove for access, minor maintenance actions, etc. The reason that removal rates are generally used as a key maintenance indicator is that they drive most of the other levels of maintenance, e.g., intermediate and depot levels, and thus the associated resources at those levels, e.g., support equipment, transportation, manpower, etc.

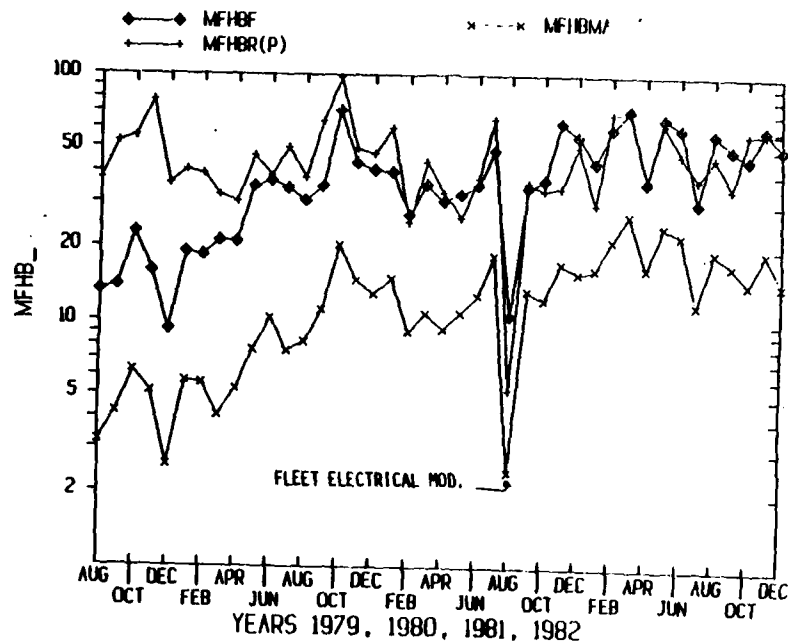


FIGURE G-1. R&M Trends for F-16

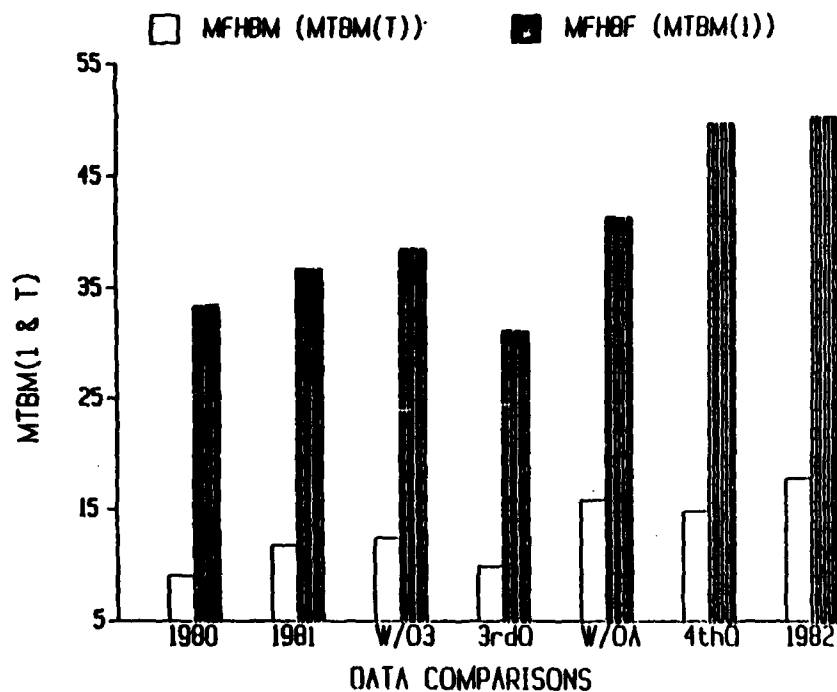
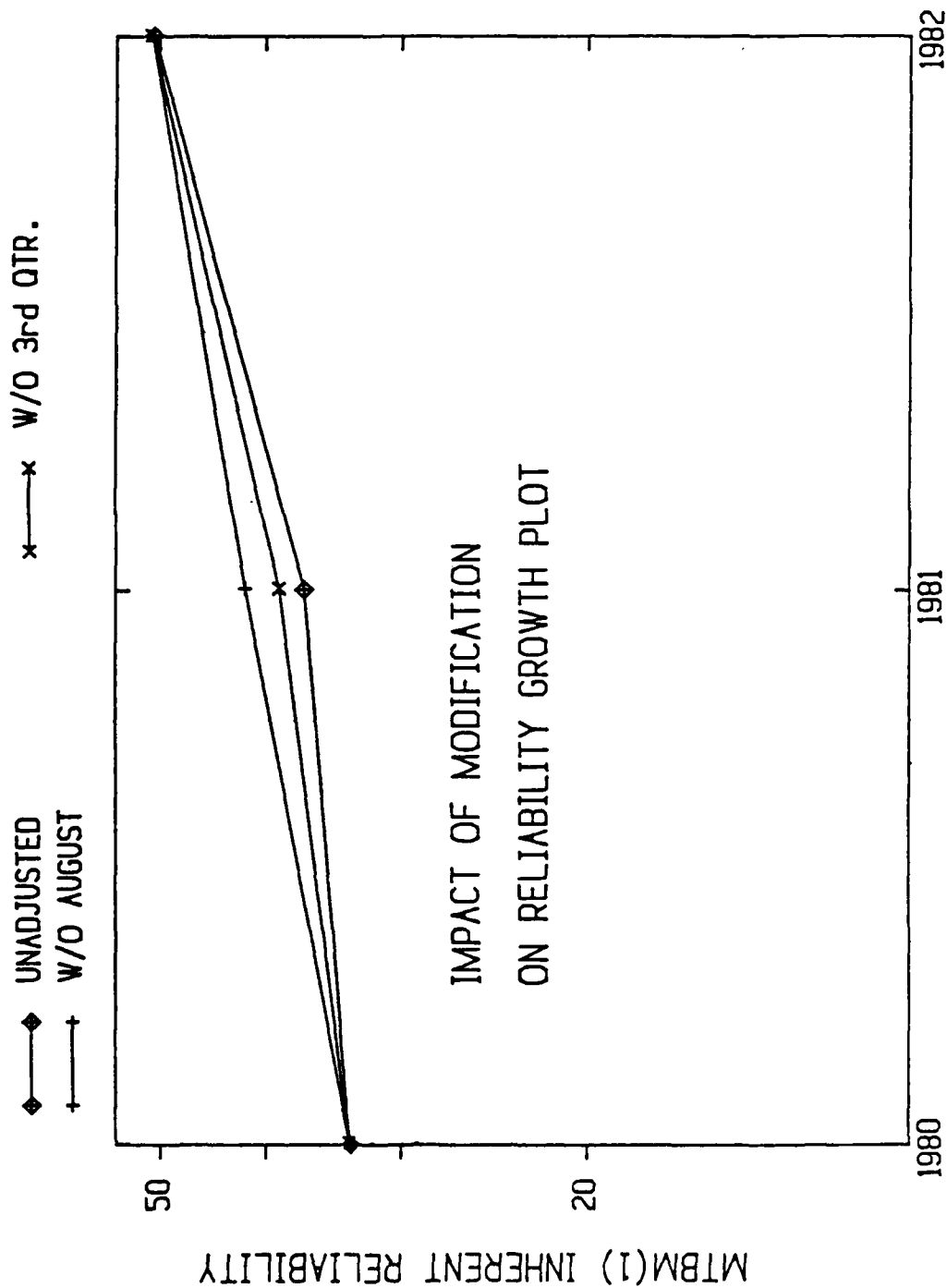


FIGURE G-2. F-16 Radar Data Example (CY 81)



YEARS 1980, 1981, 1982

FIGURE G-3. F-16 Fleet Electrical Modification

Accepting the premise that removal rate is the single most important measure, the next question is where does one get the data, especially since accuracy is very important. A review of studies of the accuracy of the Service data systems indicate that as few as 2 percent of the maintenance records are totally accurate (every single entry is precisely correct) and that 40 percent to 70 percent of the records are "functionally useful" (accurate enough to track trends). Most analysts, therefore, draw their removal data from the supply system or an off-line, manual system. Some of the pitfalls of obtaining accurate removal data are illustrated on Figs. G-4, G-5, and G-6. Figure G-4 presents data obtained from a Rand Corporation briefing as well as data from the Air Force DO56 data system. The Rand data were derived from the AFTO Form 95 log in the Avionics Intermediate Shop (AIS) at each base. The DO56 data are for all F-15/F-16 bases for the same period of time. Note that the F-15 C/D DO56B data adjusted to the same basis (per sortie versus per flying hour) is about 30 percent higher than the Rand data, while in both F-16 comparisons the DO56B data are more than 50 percent lower. Figure G-5 also uses DO56B and is the same subset of removals (i.e., without cannibalizations and remove from access) as Fig. G-4. These data show that the F-16 radar removal rate (on average) is about three times better than the next best (F-15 C/D). The chart also shows that the F-16 rate is extremely variable and consistently so. Figure G-6 is also data from a Rand briefing on the variability of demand rates on specific parts (indicated by the five-digit work unit code) both at a base as well as between bases. The message is that there are large variations at the same base over time as well as between bases. Field interviews at the bases were used to explain the variation.

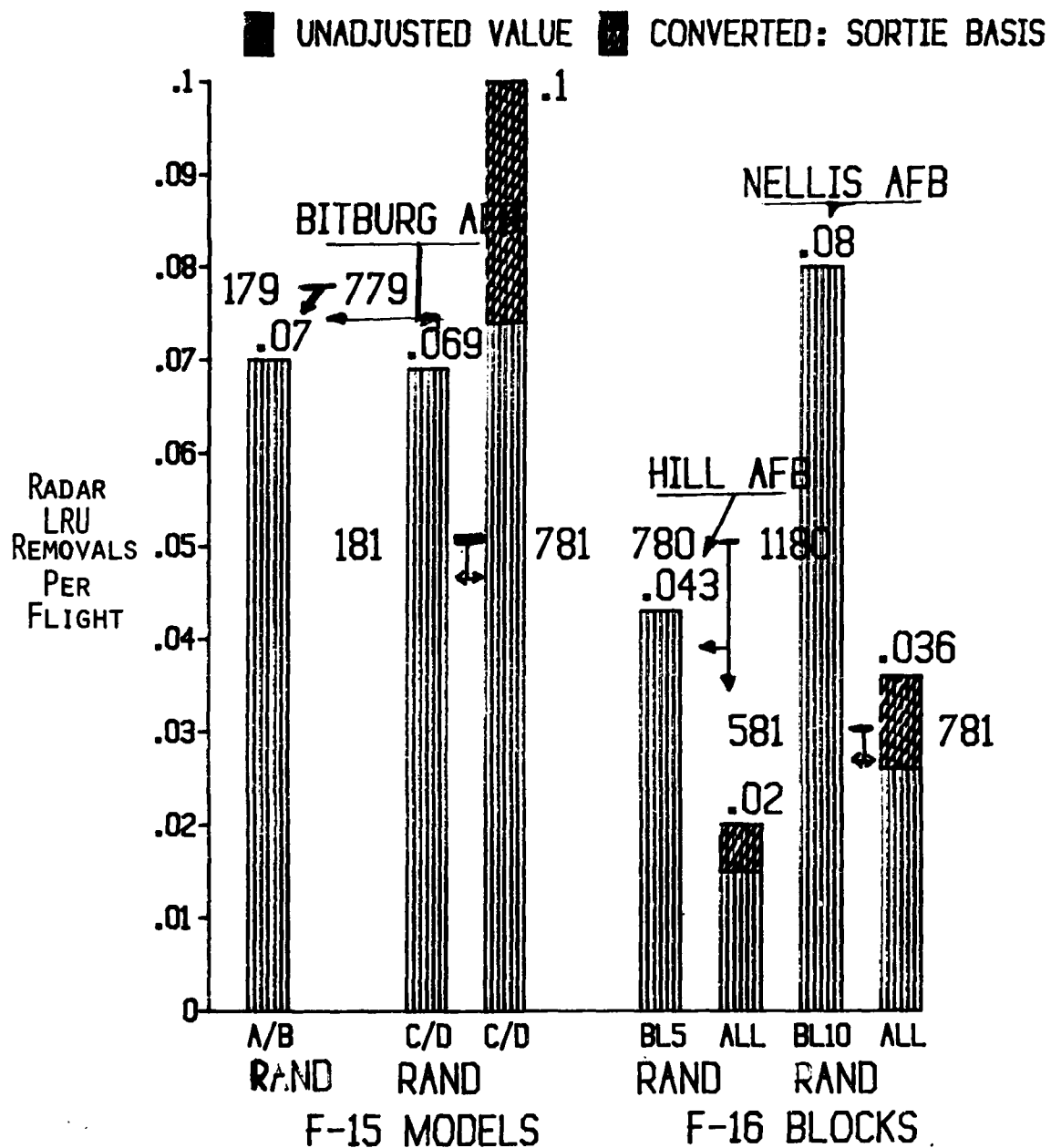


FIGURE G-4. Rand Radar Removal Data Compared to Air Force DO56B Removal Data (Adjusted)

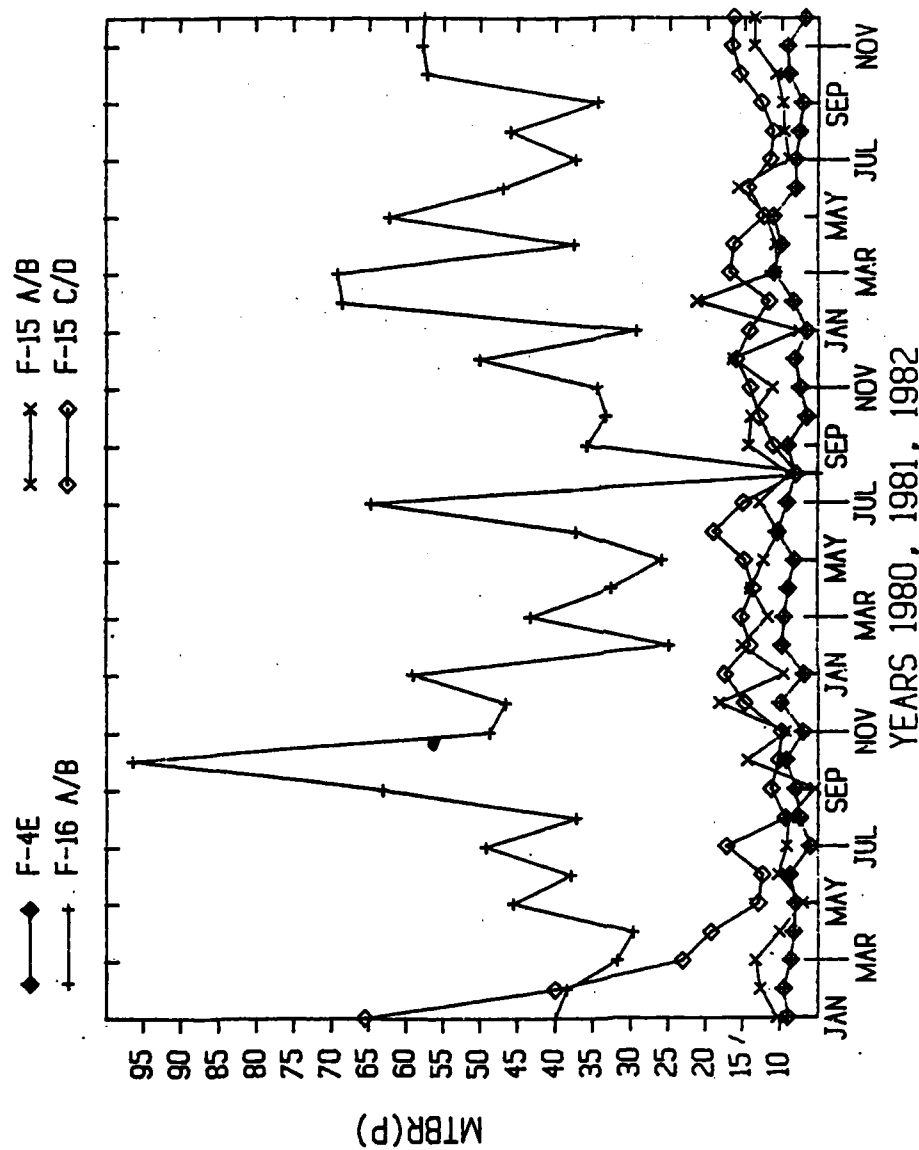


FIGURE G-5. DO56 Data: MTBR Without Cannibalizations

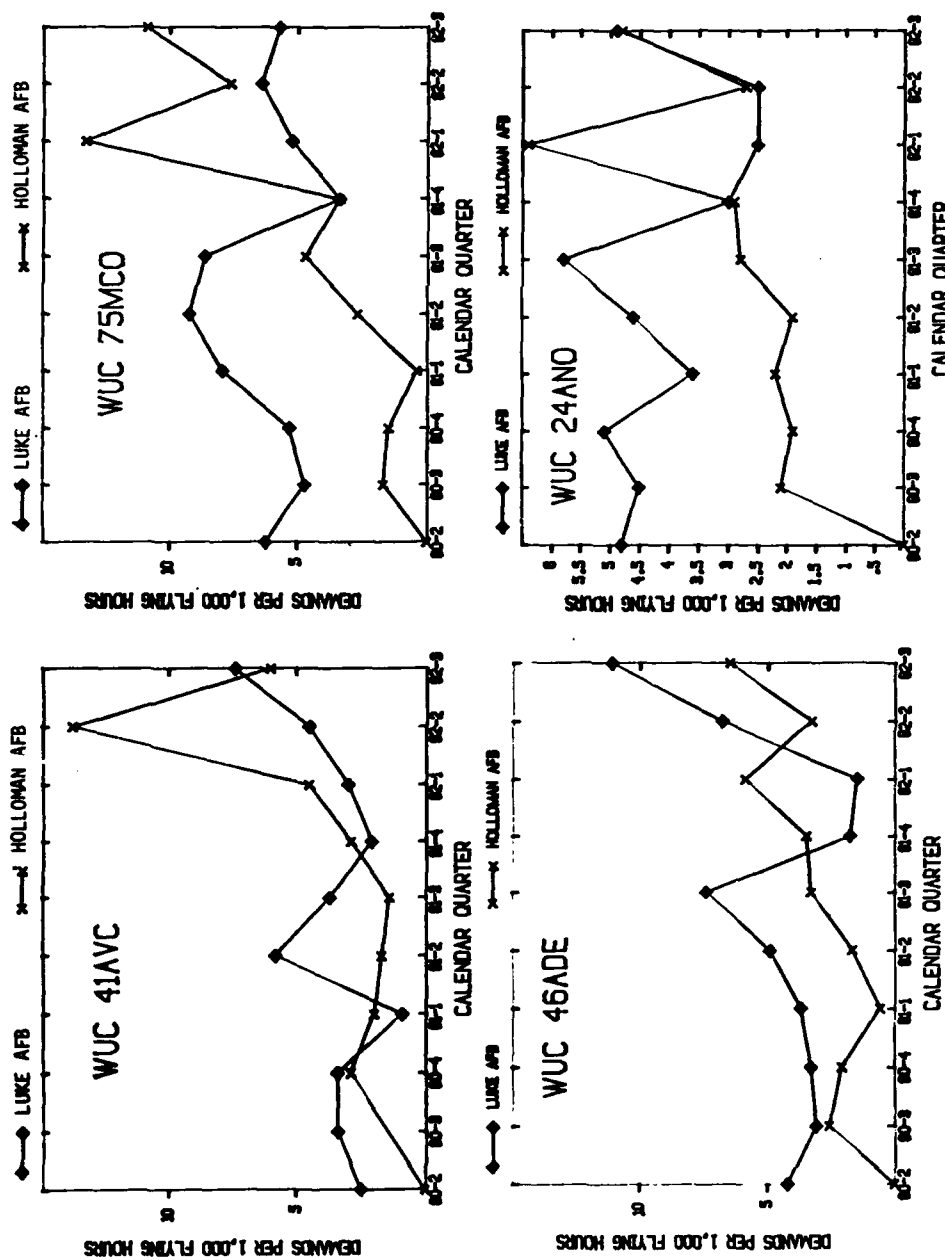


FIGURE G-6. Part Demand Rate Variation



in most cases reasonable explanations were found. The reasons varied from organizational changes to specific modifications to parts and automatic test equipment.

Given the above situation, even if the AFTO Form 95 derived data are more accurate, the manpower costs of capturing the data, which results in 3 to 6 months of data for a few bases, could be very misleading. The other two approaches have limitations as well. The D056B data are suspect as to accuracy, but easily available, while the base level supply data are likely more accurate, but require special data runs and must be captured on a base-by-base basis.

### 3. Impact of Installation of Maintenance Data Terminals at All F-16 Bases

Beginning in mid-1982, maintenance data terminals were installed at all F-16 bases. By late 1982 or early 1983, the installation was complete. During that period, based on information from the F-16 SPO, over 3,500 job control numbers that were in limbo in the data system were closed out in order to mechanize the data process. The regression of the radar MTBM(T), (see Fig. G-7), the middle line, from the low twenties to about 17 is likely a reflection of that conversion. The leveling of inherent reliability could also be affected by the conversion. The following section reflects a historical precedent for this supposition.

### 4. Impact of Installation of Data Terminals at Dover AFB for the C-5A

Figures G-8 and G-9 show the impact of automating the maintenance data process at Dover AFB, Delaware (C-5A data). At Dover, installation of terminals and the subsequent on-line editing and checking of maintenance tasks have resulted in much

822/3-10

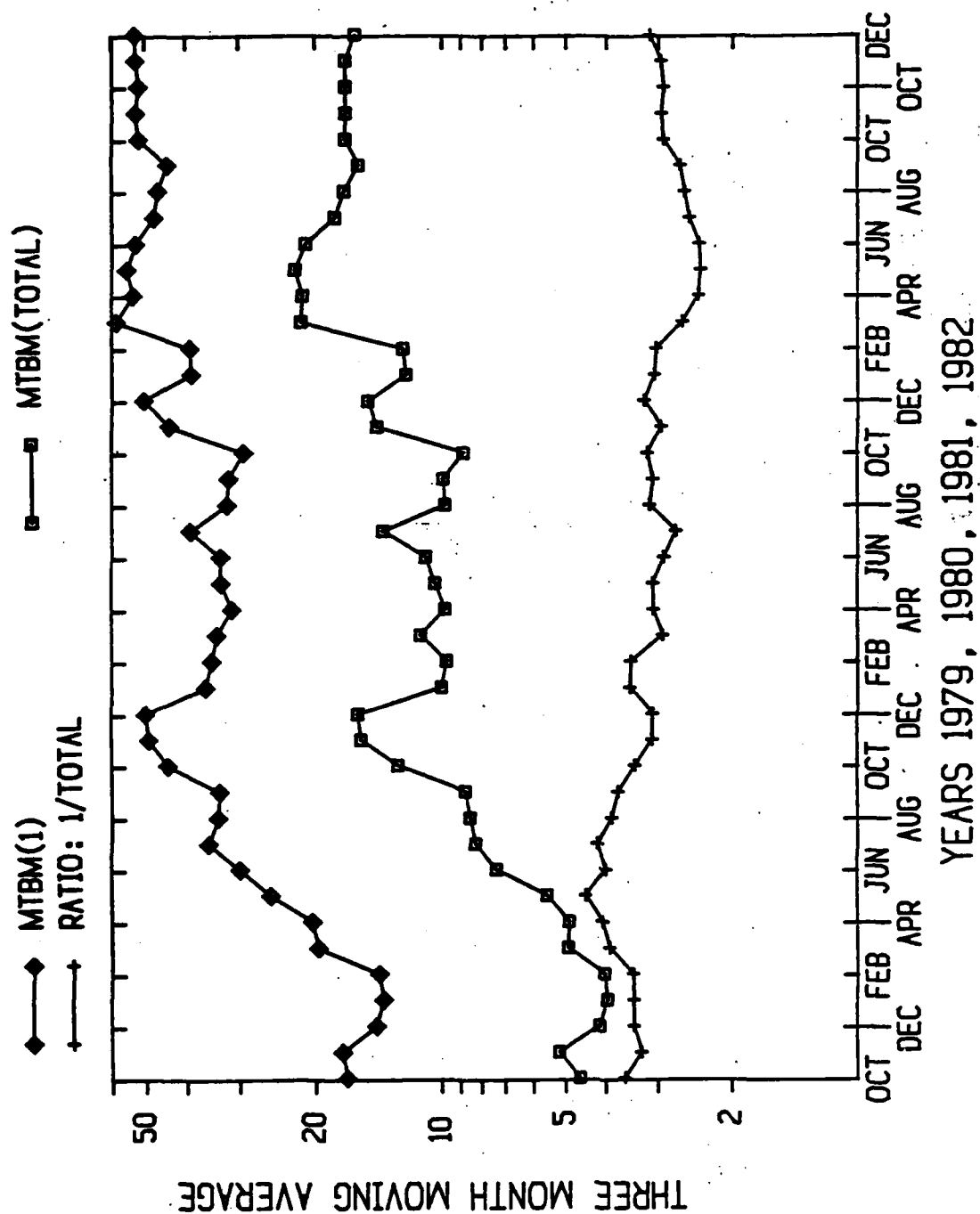


FIGURE G-7. F-16 A/B Radar (APG-66) DO56B Data

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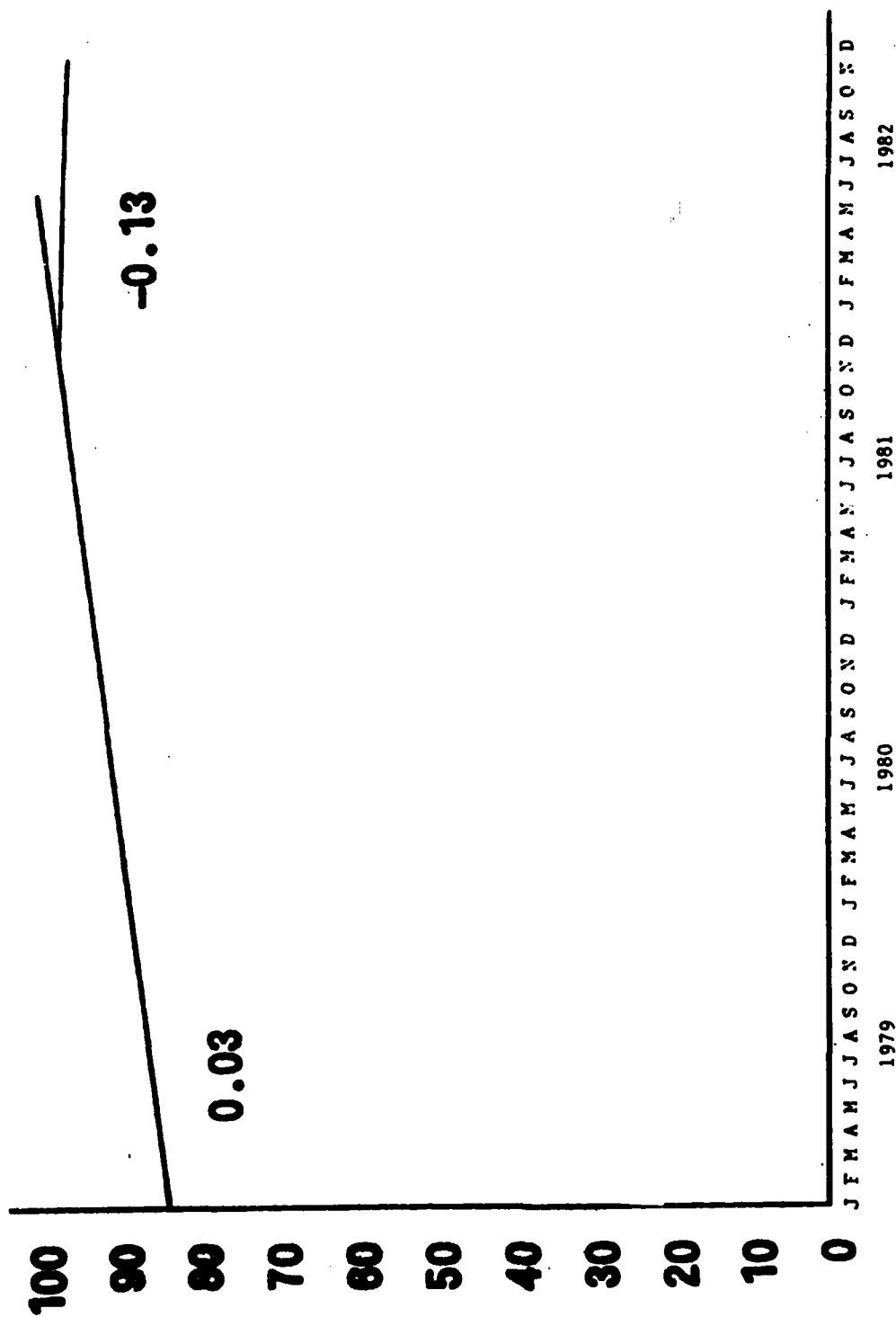


FIGURE G-8. Percent of Total Discrepancies Closed with MDC - AMS

94/14-13

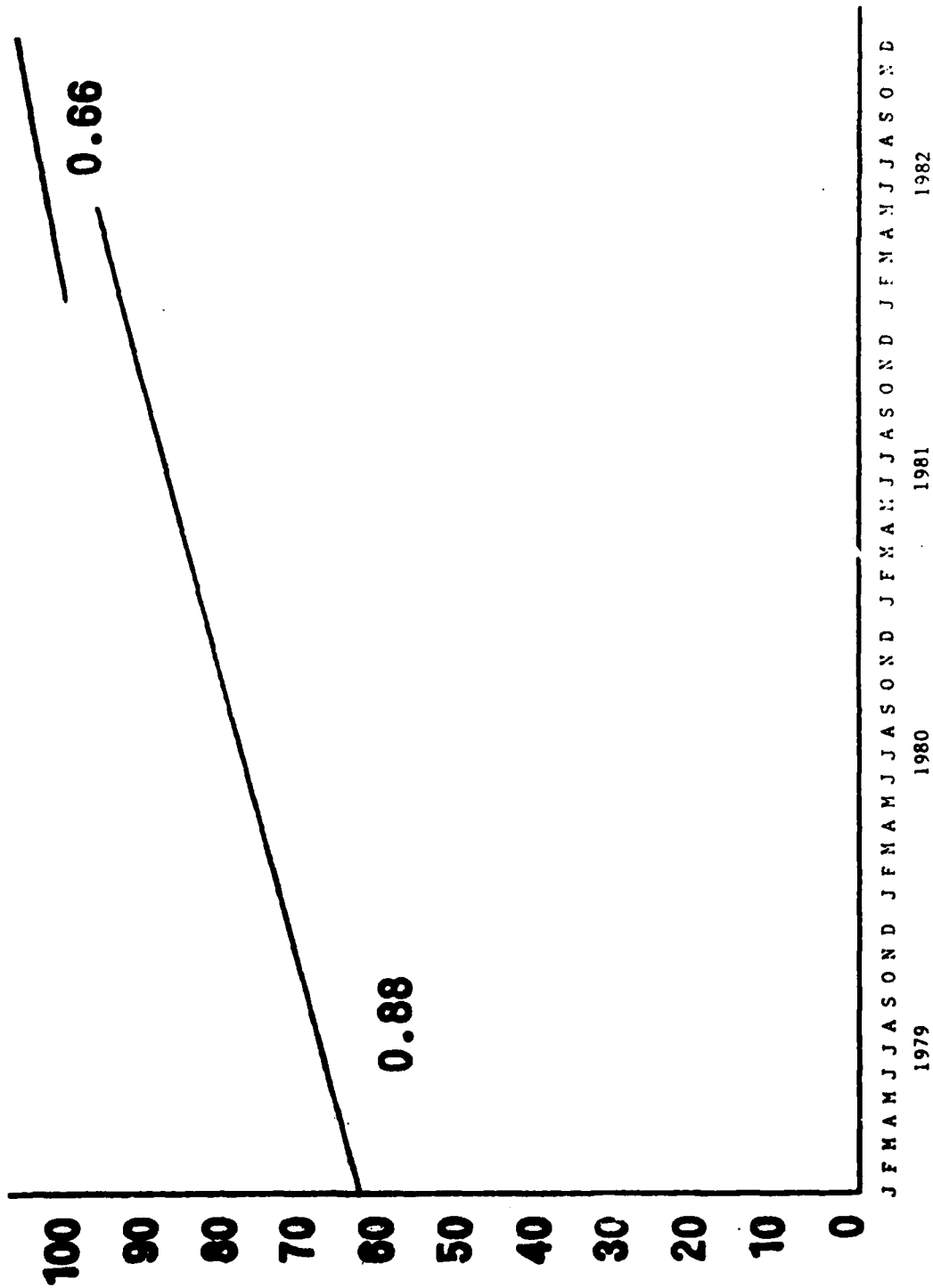


FIGURE G-9. Percent of Total Discrepancies Closed with MDC - FMS

94/14-14

more accurate data, i.e., more of the maintenance tasks are captured in the data system and the entries are much more accurate. The Automatic Maintenance System (AMS) at Dover is much further developed than the F-16 system and in fact after an initial downturn of reliability and maintainability measures at Dover AFB, due again to capturing of more and more accurate data, the R&M measures now show significant improvement, i.e, 27 percent less parts used per sortie, 33 percent increase in MTBM(T), 89 percent decrease in abort rate, and 41 percent increase in maintenance productivity. These improvements are not just data improvements, but reflect the potential for significant maintenance improvements via improved planning, scheduling and controlling, as well as providing near-real-time data to the maintenance man, allowing him to work smarter. Similar results may occur on the F-16.

#### 5. T-38 Base-to-Base Comparison of Avionics Reliability

A recent study of operational influences on avionics reliability examined, among many other variables, how the field operational MTBF of three different avionics equipments on the USAF T-38 twin jet trainer aircraft compared across nine different Air Training Command bases flying essentially the same basic pilot training program over a period of one calendar year. The results (Fig. G-10) indicated that the equipment's MTBF performance (expressed as a percentage of the average performance at all nine bases) varied from as low as 57 percent at the base with the lowest MTBF to a high of 285 percent at the base with the highest operational MTBF. Similarly, when the combined results of the composite performances of all three equipments (UHF Radio, TACAN, Inertial Platform) were compared, similar differences of 78 percent and 163 percent were observed. Upon more detailed investigation, the conclusions drawn were that the differences observed were due primarily to differences in the maintenance skill levels across the nine different bases.

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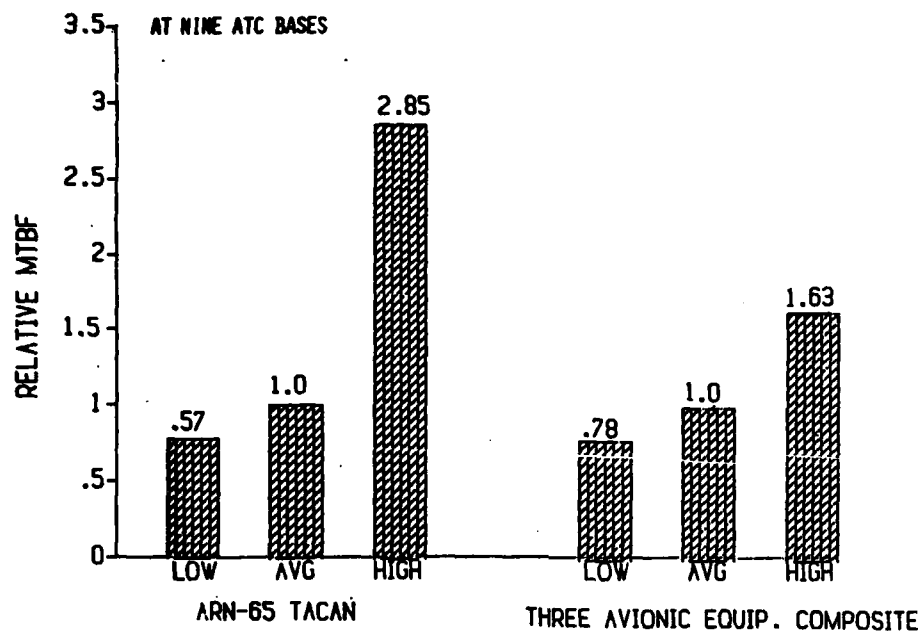


FIGURE G-10. Comparison of T-38 Avionics MTBF

#### 6. Field Reliability Performance Comparisons

On a number of occasions during the course of the study, briefings were given based on data compiled to demonstrate a particular point. Figure G-11 represents field reliability data from official sources for the APG-63, APG-65, and APG-66 radars on the F-15, F-18, and F-16 aircraft, respectively. This internally developed chart highlights all too well how the same data may be used to "prove" a variety of things.

# FIELD RELIABILITY PERFORMANCE

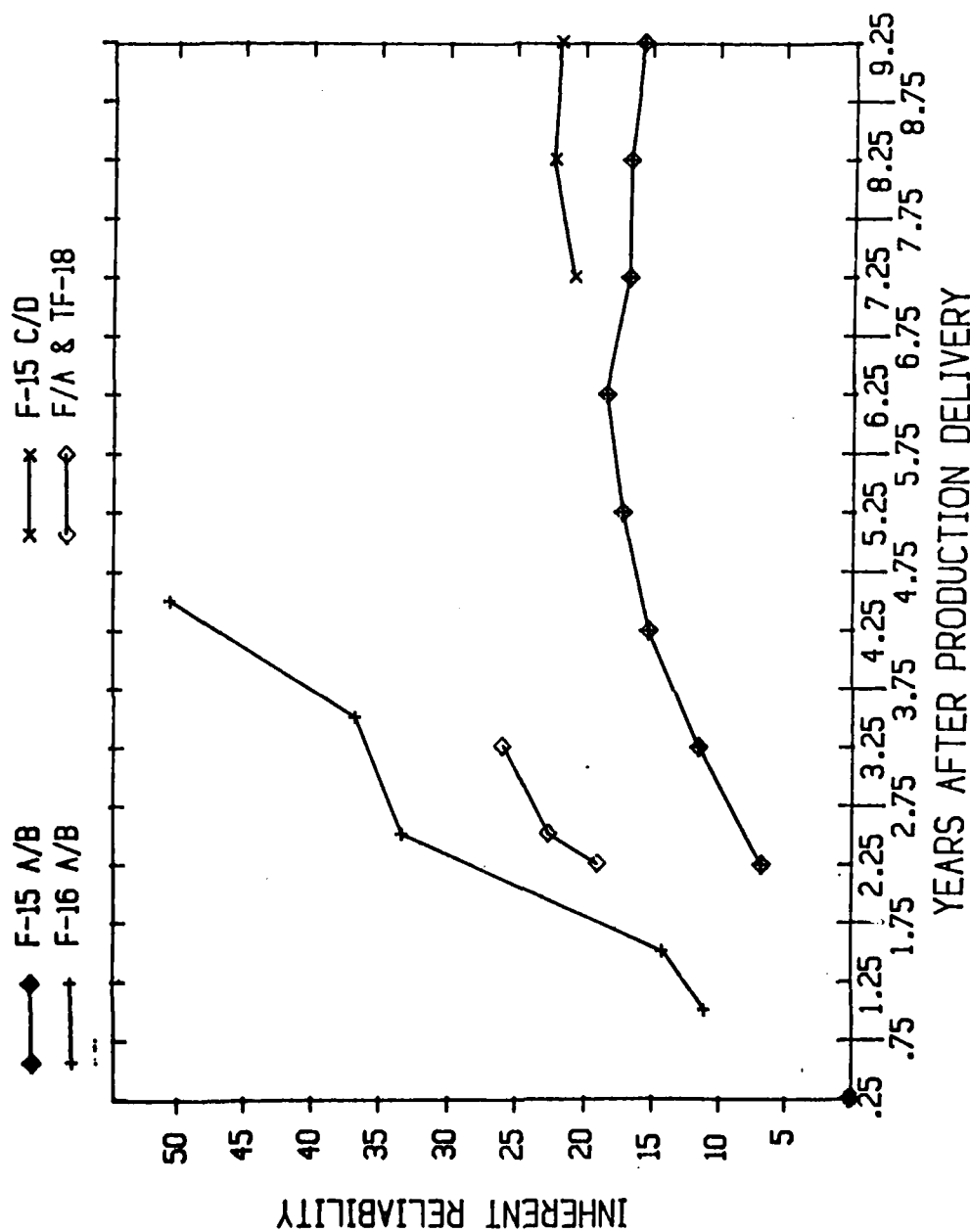


FIGURE G-11. Radar Field Reliability Performance

822/3-16

For example, one might conclude that the rapid and sustained growth for the APG-66 radar reliability was due to the fact that field usage began very soon after the first production delivery. This very short time from production to field use, coupled with high production rates, enabled the contractor to learn of field problems early and to correct them, which led to large improvements in reliability.

Another point that can be made is that the Navy's "New Look" program is probably working since initial field values for APG-65 reliability are considered quite good. A part of the "New Look" program calls for early reliability development testing. As can be seen in Figure G-12, the APG-65 did have a significant number of growth test hours during FSD. That could have contributed to this high initial field reliability, even though others have pointed out that very little new was learned during the reliability growth test phase.

Still another point that looks obvious is the visual presentation of the APG-63 C/D as compared to the APG-63 A/B. One could conclude that as the C/D received the attention, the A/B reliability declined, or that the C/D represents normal growth of an extended A/B radar program.

All of these observations are made based on data plotted on a linear scale, even though we all know that the scale should be logarithmic when this type of comparison is made. The conclusions reached from this chart, however, may be valid for the intended purpose, but as with all the other data examples that precede this one, more information is probably needed before any judgment is made.



# R TESTING UNDER ENVIRONMENT

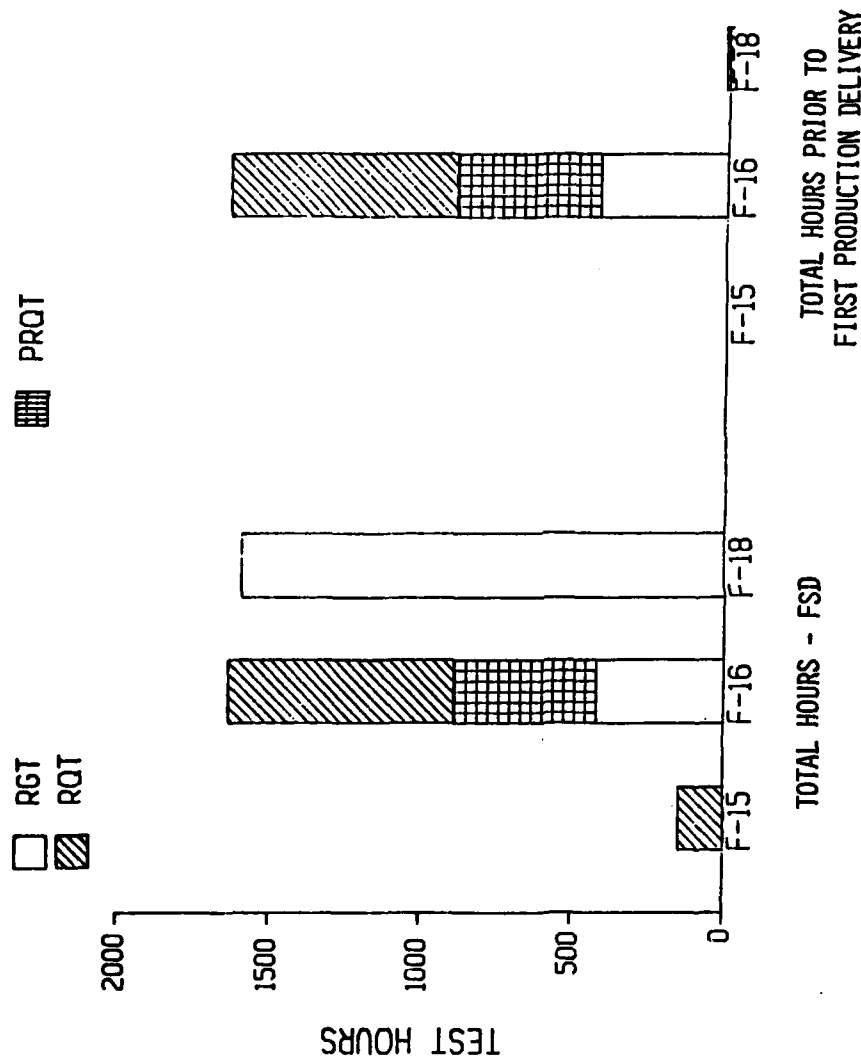


FIGURE G-12. Reliability Testing Under Environment

822/3-18

## B. USE OF SERVICE DATA SYSTEMS

### 1. General

During the course of the study significant differences in R&M performance were noted, depending on how the data were sliced and how well other confounding factors were discovered, investigated and understood. The utility of the data depends on the question to be answered. As long as trending data can be used to answer the question, the Service data systems, if used cautiously and properly, can provide useful information. The six examples previously discussed demonstrate some of the pitfalls: impact of events such as the F-16 Fleet Electrical Modification; potential inaccuracies due to small, limited sample sizes as illustrated in the F-16 and F-15 radar removal rate variation, both between and within operational locations; significant changes in basic R&M measures due to changes in data collection/reporting procedures such as at Dover AFB, Delaware and the F-16 data terminals; the impact of other support elements such as training and skill levels on the (apparent) reliability (operational MTBF) of equipment illustrated in the T-38 avionics example. The utility of the data for making engineering decisions like "what to fix," when all indicators say the reliability is too low, is suspect. As illustrated above, the real problem could be unrelated to the reliability of the equipment. It could be a reflection of poor training; a requirement for skills beyond the level of typical maintenance personnel, poor technical orders; the use of the equipment outside of its designed limitations, inadequate support equipment, poor fault detection and/or fault isolation capability, etc. Acquiring data which have the attributes required to analyze and pinpoint the cause of such problems presents a dilemma. The principal intent of the systems is to determine resource requirements and to identify problems. The question is, to what degree should the data systems provide the information to support analysis of

822/3-19

resource requirements and to determine specifically what needs to be done to fix problems. The data analysis problems discussed above provide some insight into the lack of current capability. The shortfall, with the exception of the diagnostics area, is not one of more needed data elements--it is instead missing data and inaccuracies of reported data. Diagnostics data need improvements across the board.

## 2. Solutions to the Data Dilemma

Two solutions to the data dilemma have been examined. First, the Army approach, i.e., the sample data collection system (SDC), which includes collection of logistics data via a sampling system as well as a very detailed data collection during the acquisition process via the RAMLOG Data System, and second, the Air Force Automated Maintenance System (AMS) for the C-5A aircraft at Dover AFB, Delaware.

The Army SDC system evolved from cognizance of the same problems described in the limitations above. In the Army case, they were faced with another compounding dimension, namely, dispersal of the maintenance process (e.g., five levels of maintenance versus three for the Air Force). Their solution was to use "dedicated" data collectors to collect accurate logistics data via a sampling approach. Since data are their business, they tend to be highly motivated to ensure that the data are accurate and timely. In addition, the data collection effort can be adjusted in frequency, number of locations sampled, and degree of detail. The RAMLOG system, developed during the Blackhawk helicopter program, has also proven to be an excellent data system for the acquisition process. The Army SDC system is proving to be an excellent approach for determining resource requirements, identifying problems areas and providing detailed accurate data required to support analysis.

The Air Force AMS approach is at the other end of the spectrum of solutions to the data dilemma. AMS is a computer-based real-time system which uses a central data base concept. The central

822/3-20

data base, located at the Oklahoma City Air Logistics Center, (OC-ALC) is connected to on-line terminals at Dover AFB, Delaware (over 100 terminals in maintenance shops, job control, wing headquarters, etc.) as well as OC-ALC and San Antonio ALC. The system is currently being extended to other C-5A bases at Altus AFB, OK and Travis AFB, CA. AMS adds at least two dimensions to the utility of data systems. In addition to providing superb data for resource requirements, problem identification, and data to support analysis, the system provides real-time data for planning, scheduling and controlling of the maintenance process, e.g., jobs are not scheduled until all of the necessary resources (people, parts and material, support equipment), as well as the end item to be fixed (aircraft or line replaceable unit (LRU) are available. The benefits accrued from this added dimension are illustrated in Fig. G-13; home station logistics caused delayed departures and Fig. G-14, increase in fully mission capable rate, while they may appear to be small have had the effect of providing two to three more aircraft available for sortie generation. The second added dimension, provided by AMS, is real-time availability of detailed accurate data for all levels, not only for analysis but also for the day-to-day maintenance process. For example, prior to departing the shop for a task, maintenance personnel are provided a printed history of the system/subsystem on the aircraft that they are going to work on. The effects of this powerful capability are dramatic, e.g., reduction of about 20 percent in spare parts used per sortie flown, a significant reduction in repeat malfunctions and even more critical, the data now provide a readily available tool which is very useful to the people who report it (the basic truth of good data systems--the data are useful to those who report it). AMS is a powerful, proven tool that has provided enormous benefits for the C-5As at Dover. However, unlike the Army SDC system, which is available

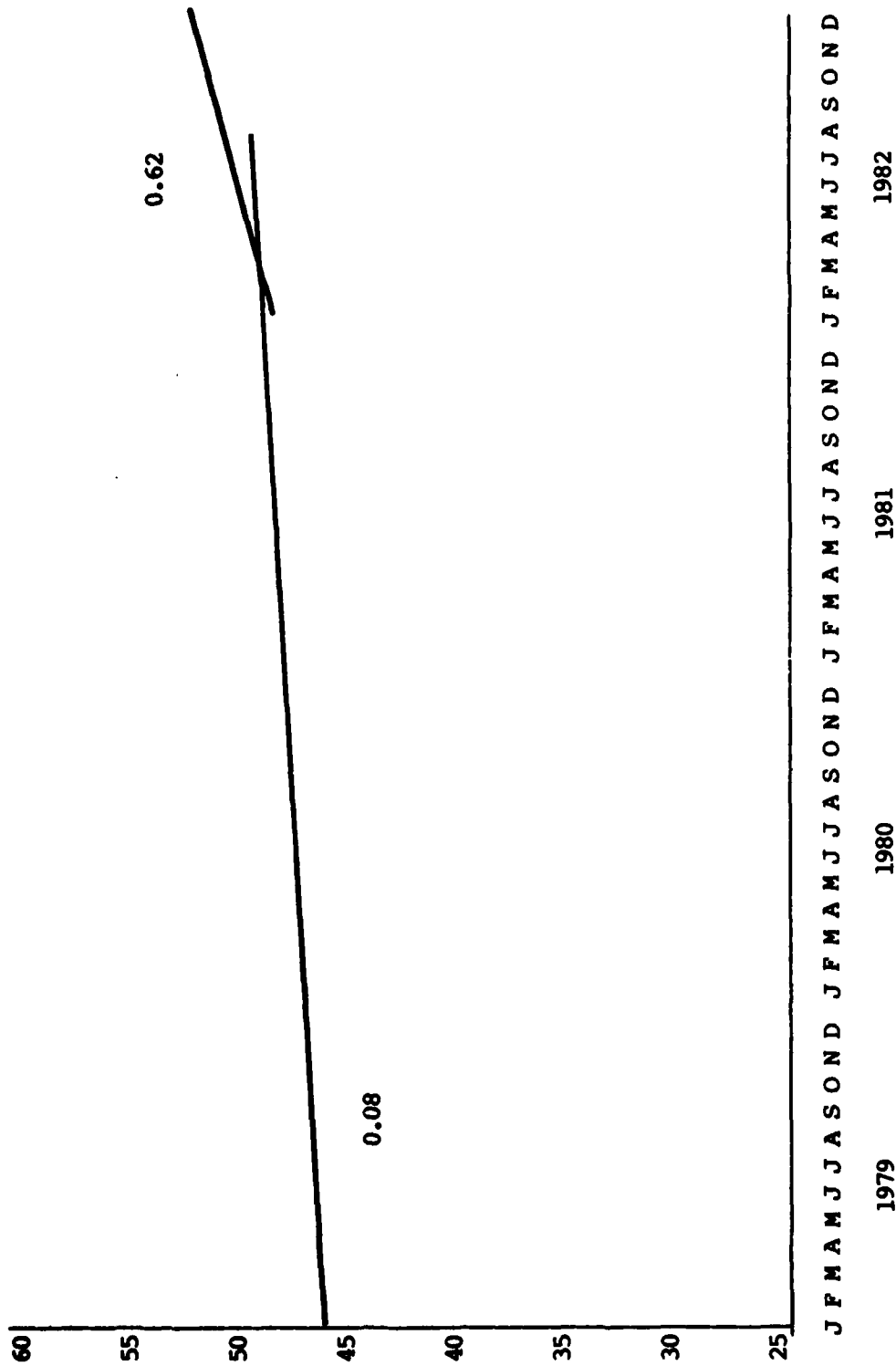


FIGURE G-14. Fully Mission Capable Rate

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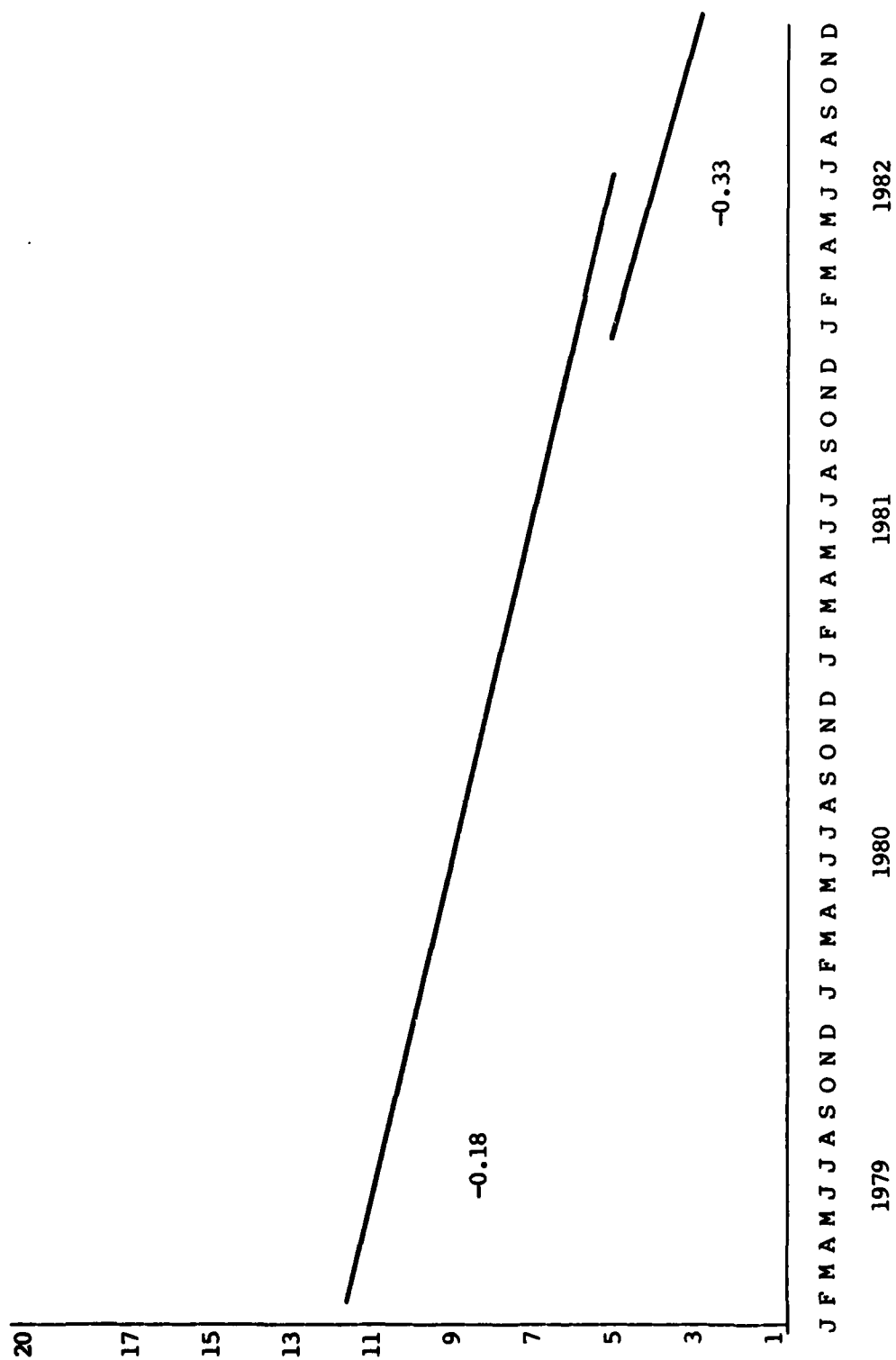


FIGURE G-13. Home Station Logistics Caused Delay Departures

Army-wide AMS is fully operational only at Dover AFB (soon to be operational at the remaining C-5A bases).

Both SDC and AMS provide useful solutions to the data dilemma. AMS provides added dimensions and should be considered as a model for future data systems. SDC provides good, accurate data, but if the data are not being collected as a normal part of the sampling process, time is required to request, get approval, collect, process, and analyze the data.

While the Army SDC provides the best Service-wide approach today, it would appear, based on Army, Navy, and Air Force projected logistics requirements and Year-2000 concepts, that data systems modeled around the AMS approach should be sought as the data systems of the future.

APPENDIX H

BACK-UP DATA



## BACK-UP DATA

This appendix documents data from official Air Force and Navy sources that was used for various analysis throughout the study period. The Air Force data is from the D056B and D056T reports and the Navy data is from 3M.

1	A	B	C	D	E	F	G	H	I	J	K	L
1	FILE NAME	TF/A-18	RADAR (APG-65)	3M DATA (R&M SUMMARY)	NAMSO 4790-A7298-01							
2	REVISED	AUGUST 12										
3	DATE	FLIGHT	TOT MAINT	MLL RPR	TOTAL	UNSKD	MAINT MH	MAINT MH	MAINT HRS	EMT PER		
4	FROM-TO	HOURS	ACTIONS	ACTIONS	FAILURES	MAINT MH	PER FH	PER FH	PER MA	MAINT ACT		
5												
6	482-982	3677	534	33	178	20.66	4131	1.123470	7.74	5.4		
7	582-1082	3936	525	35	175	22.49	4117	1.045986	7.84	5.7		
8	582-1182	4139	542	42	183	22.62	4186	1.011355	7.72	5.7		
9	782-1282	4127	543	37	179	23.06	4087	.9903077	7.53	5.8		
10	882-183	4260	581	38	188	22.66	4085	.9589202	7.03	5.5		
11	982-283	4275	595	39	178	24.02	3861	.9031579	6.49	5.1		
12	1082-583	4517	667	38	171	26.42	4285	.9486385	6.42	4.8		

H-4

1	A	B	C	D	E	F	G	H	I	J	K	L
1	FILE NAME	TF/A-18	RADAR (APG-65)	3M DATA (R&M SUMMARY)	NAMSO 4790-A7298-01							
2	REVISED	AUGUST 12										
3	DATE	FLIGHT	TOT MAINT	MLL RPR	TOTAL	UNSKD	MAINT MH	MAINT MH	MAINT HRS	EMT PER		
4	FROM-TO	HOURS	ACTIONS	ACTIONS	FAILURES	MAINT MH	PER FH	PER FH	PER MA	MAINT ACT		
5												
6	482-982	1606	70	6	6	267.67	95	.0591532	1.36	.8		
7	582-1082	1617	240	14	71	22.77	1883	1.164502	7.85	6.1		
8	1682-1182	1603	242	12	70	22.90	1999	1.247037	8.26	6.7		
9	782-1282	1535	220	7	55	27.91	1838	1.197394	8.35	6.9		
10	1882-183	1729	256	4	70	24.70	2053	1.187392	8.02	6.7		
11	982-283	1863	267	3	72	25.88	2026	1.087493	7.59	6.2		
12	1082-583	2093	307	2	83	25.22	2218	1.059723	7.22	5.8		

FIGURE H-1. APG-65 Radar Maintenance Summary

FILE NAME	A	B	C	D	E	F	G	H	I	J	K
1 F/A-18 RADAR (APG-65)											
2 TF/A-18(COMBINED)											
3 REVISED AUGUST 12											
4 DATE											
5 FROM-TO											
6	482-982	5283	604	8.75	39	184	28.71	4226	.80	7.00	4.87
7	582-1082	5553	765	7.26	49	246	22.57	6000	1.08	7.84	5.83
8	1682-1182	5742	784	7.32	54	253	22.70	6185	1.08	7.89	6.01
9	782-1282	5662	763	7.42	44	234	24.20	5925	1.05	7.77	6.12
10	1882-183	5989	837	7.16	42	258	23.21	6138	1.02	7.33	5.87
11	982-283	6138	862	7.12	42	250	24.55	5887	.96	6.83	5.44
12	1082-383	6610	974	6.79	40	254	26.02	6503	.98	6.68	5.12

H-5

FILE NAME	A	B	C	D	E	F	G	H	I	J	K
1 F-18 CUMULATIVE RELIABILITY DATA (VFA-125 ONLY)											
2 SOURCE: HUGHES-CHARLES FARRELL-8/8/83											
3 REVISED DATE AUGUST 12											
4 FILENAME: F-18 CUM											
5 YEAR											
6 PERIOD											
7	1981	ALL	922	922	6.826545	43	43	21.44	21.44		
8	1982	JAN-FEB	796	1718	7.448916	32	75	22.91	24.88		
9		MAR-APR	726	2444	7.801391	32	107	22.84	22.69		
10		MAY-JUN	884	3328	8.110127	34	141	23.60	26.00		
11		JUL-AUG	1181	4509	8.413831	43	184	24.51	27.47		
12		SEP-OCT	1427	5936	8.688791	34	218	27.23	41.97		
13		NOV-DEC	1403	7339	8.900958	39	257	28.56	35.97		
14	1983	JAN-FEB	1885	9224	9.129564	56	313	29.47	33.66		
15		MAR-APR	2295	11519	9.351753	65	378	30.47	35.31		
16		MAY-JUN	2372	13891	9.538996	56	434	32.01	42.36		
17											

FIGURE H-2. APG-65 Radar Maintenance Summary

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
2	1979F16A/B	DISK DATA	FILENAME	DATE	JULY 12, 1983	MIC 7A00X	LINE 4, 5																	
3	DISK #4																							
4	DATE	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME
5	DATE	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME
6	JAN																							
7	FEB																							
8	MAR																							
9	APR																							
10	MAY																							
11	JUN																							
12	JUL																							
13	AUG	33	479	36	1	149	9.00	3	367	149	1	12	13	36.85	13.31	479	3.2148	112	.0271398747	479				
14	SEP	39	779	56	1	185	13.67	3	399	89	1	14	15	51.93	13.91	779	4.2108	129	.0192554557	779				
15	OCT	47	1095	48	1	173	16.81	9.00	3	484	189	9	11	20	54.75	22.81	1095	6.3295	124	.0182648402	1095			
16	NOV	58	1069	67	1	207	17.21	10.00	3	627	211	3	11	14	76.36	15.96	1069	5.1643	140	.0130963517	1069			
17	DEC	63	955		3	370	14.31	8.00	2	983	230	4	23	27	35.37	9.27	955	4.377	2.5811	264	.0282722513	955		
18																								
19	ANG	TOTAL	TOTAL	TOTAL	TOTAL	ANG	ANG	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL
20	1ST QTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	2ND QTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	3RD QTR	36	1258	0	92	1	334	13.67	3.77	3	766	238	2	0	26									
23	4TH QTR	56	3119	0	218	4	750	14.31	4.16	5	2094	630	16	0	45									
24	YEAR	46	4377	0	310	5	1084	14.12	4.04	8	2860	968	18	0	71									
25	** THREE MONTH MOVING AVERAGE																							

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
2	1980F16A/B	DISK DATA	FILENAME	DATE	JULY 12, 1983	MIC 7A00X	LINE 4, 5																	
3	DISK #4																							
4	DATE	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	
5	DATE	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	TIME	
6	JAN																							
7	FEB																							
8	MAR																							
9	APR																							
10	MAY																							
11	JUN																							
12	JUL																							
13	AUG	121	2366	69	2	301	33.37	17.00	5	1680	568	10	27	37.21	30.40	2366	7.63	241	.0202874049	2366				
14	SEP	125	2493	82	2	301	33.03	17.00	2	1228	338	2	34	36	63.22	35.02	2493	8.28	217	.0158172232	2493			
15	OCT	222	4337	61	1	212	43.78	29.00	2	1253	274	3	42	45	96.38	71.10	4337	20.46	150	.0103758358	4337			
16	NOV	235	3898	90	5	263	48.66	36.00	6	1617	567	12	68	80	48.73	43.31	3898	25.745	168	.0205233453	3898			
17	DEC	259	3497	86	4	268	49.50	38.00	6	1730	648	13	62	75	46.63	40.66	3497	29.242	178	.0214669545	3497			
18																								
19	ANG	TOTAL	TOTAL	TOTAL	TOTAL	ANG	ANG	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	
20	1ST QTR	80	4174	0	213	6	840	19.60	4.97	17	2581	711	5	0	111									
21	2ND QTR	108	6201	0	209	4	840	29.67	7.38	20	3621	912	9	0	157									
22	3RD QTR	127	7135	0	216	3	814	33.03	8.77	19	4400	1167	14	0	137									
23	4TH QTR	239	11732	0	227	10	743	49.50	15.79	6	4600	1489	28	0	172									
24	YEAR	138	29242	0	875	23	3237	33.42	9.03	62	15202	4279	56	0	577									
25	** THREE MONTH MOVING AVERAGE																							

FIGURE H-3. APG-66 Radar Maintenance Summary

1 1961 PLAN/DISG DATA										2 1962 PLAN/DISG DATA										3 1963 PLAN/DISG DATA										4 1964 PLAN/DISG DATA										5 1965 PLAN/DISG DATA										6 1966 PLAN/DISG DATA										7 1967 PLAN/DISG DATA										8 1968 PLAN/DISG DATA										9 1969 PLAN/DISG DATA										10 1970 PLAN/DISG DATA										11 1971 PLAN/DISG DATA										12 1972 PLAN/DISG DATA										13 1973 PLAN/DISG DATA										14 1974 PLAN/DISG DATA										15 1975 PLAN/DISG DATA										16 1976 PLAN/DISG DATA										17 1977 PLAN/DISG DATA										18 1978 PLAN/DISG DATA										19 1979 PLAN/DISG DATA										20 1980 PLAN/DISG DATA										21 1981 PLAN/DISG DATA										22 1982 PLAN/DISG DATA										23 1983 PLAN/DISG DATA										24 1984 PLAN/DISG DATA										25 1985 PLAN/DISG DATA										26 1986 PLAN/DISG DATA										27 1987 PLAN/DISG DATA										28 1988 PLAN/DISG DATA										29 1989 PLAN/DISG DATA										30 1990 PLAN/DISG DATA										31 1991 PLAN/DISG DATA										32 1992 PLAN/DISG DATA										33 1993 PLAN/DISG DATA										34 1994 PLAN/DISG DATA										35 1995 PLAN/DISG DATA										36 1996 PLAN/DISG DATA										37 1997 PLAN/DISG DATA										38 1998 PLAN/DISG DATA										39 1999 PLAN/DISG DATA										40 2000 PLAN/DISG DATA										41 2001 PLAN/DISG DATA										42 2002 PLAN/DISG DATA										43 2003 PLAN/DISG DATA										44 2004 PLAN/DISG DATA										45 2005 PLAN/DISG DATA										46 2006 PLAN/DISG DATA										47 2007 PLAN/DISG DATA										48 2008 PLAN/DISG DATA										49 2009 PLAN/DISG DATA										50 2010 PLAN/DISG DATA										51 2011 PLAN/DISG DATA										52 2012 PLAN/DISG DATA										53 2013 PLAN/DISG DATA										54 2014 PLAN/DISG DATA										55 2015 PLAN/DISG DATA										56 2016 PLAN/DISG DATA										57 2017 PLAN/DISG DATA										58 2018 PLAN/DISG DATA										59 2019 PLAN/DISG DATA										60 2020 PLAN/DISG DATA										61 2021 PLAN/DISG DATA										62 2022 PLAN/DISG DATA										63 2023 PLAN/DISG DATA										64 2024 PLAN/DISG DATA										65 2025 PLAN/DISG DATA										66 2026 PLAN/DISG DATA										67 2027 PLAN/DISG DATA										68 2028 PLAN/DISG DATA										69 2029 PLAN/DISG DATA										70 2030 PLAN/DISG DATA										71 2031 PLAN/DISG DATA										72 2032 PLAN/DISG DATA										73 2033 PLAN/DISG DATA										74 2034 PLAN/DISG DATA										75 2035 PLAN/DISG DATA										76 2036 PLAN/DISG DATA										77 2037 PLAN/DISG DATA										78 2038 PLAN/DISG DATA										79 2039 PLAN/DISG DATA										80 2040 PLAN/DISG DATA										81 2041 PLAN/DISG DATA										82 2042 PLAN/DISG DATA										83 2043 PLAN/DISG DATA										84 2044 PLAN/DISG DATA										85 2045 PLAN/DISG DATA										86 2046 PLAN/DISG DATA										87 2047 PLAN/DISG DATA										88 2048 PLAN/DISG DATA										89 2049 PLAN/DISG DATA										90 2050 PLAN/DISG DATA										91 2051 PLAN/DISG DATA										92 2052 PLAN/DISG DATA										93 2053 PLAN/DISG DATA										94 2054 PLAN/DISG DATA										95 2055 PLAN/DISG DATA										96 2056 PLAN/DISG DATA										97 2057 PLAN/DISG DATA										98 2058 PLAN/DISG DATA										99 2059 PLAN/DISG DATA										100 2060 PLAN/DISG DATA										101 2061 PLAN/DISG DATA										102 2062 PLAN/DISG DATA										103 2063 PLAN/DISG DATA										104 2064 PLAN/DISG DATA										105 2065 PLAN/DISG DATA										106 2066 PLAN/DISG DATA										107 2067 PLAN/DISG DATA										108 2068 PLAN/DISG DATA										109 2069 PLAN/DISG DATA										110 2070 PLAN/DISG DATA										111 2071 PLAN/DISG DATA										112 2072 PLAN/DISG DATA										113 2073 PLAN/DISG DATA										114 2074 PLAN/DISG DATA										115 2075 PLAN/DISG DATA										116 2076 PLAN/DISG DATA										117 2077 PLAN/DISG DATA										118 2078 PLAN/DISG DATA										119 2079 PLAN/DISG DATA										120 2080 PLAN/DISG DATA										121 2081 PLAN/DISG DATA										122 2082 PLAN/DISG DATA										123 2083 PLAN/DISG DATA										124 2084 PLAN/DISG DATA	
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1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	1979716A	100648	DATA	ONE	DATE	PREPARED/REVISED	DATE	JUNE 6, 1963	MUC	7440X															
2	DATE	PREPARED/REVISED	DATE	JUNE 6, 1963	MUC	7440X																			
3	INDEX	83																							
4	DATE	CP	TIME	AND	HAIR ACTION	HAIR TYPE 1	TOTAL	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION
5	DATE	CP	TIME	AND	HAIR ACTION	HAIR TYPE 1	TOTAL	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION
6	JAN	18	251	307	1	108	12.00	4.00	3	222	54														
7	FEB	21	387	35	1	108	12.00	4.00	3	222	54														
8	MAR	31	596	31	1	108	12.00	4.00	3	222	54														
9	APR	20	644	20	1	108	12.00	4.00	3	222	54														
10	MAY	36	547	71	1	230	15.00	4.00	2	544	136														
11	JUN																								
12	JUL																								
13	AUG																								
14	SEP																								
15	OCT																								
16	NOV																								
17	DEC																								
18	TOTAL																								
19	1ST QTR																								
20	2ND QTR																								
21	3RD QTR																								
22	4TH QTR																								
23	YEAR																								
24	THREE MONTH MOVING AVERAGE																								
25	THREE MONTH MOVING AVERAGE																								

H-8

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	1980716A	100648	DATA	ONE	DATE	PREPARED/REVISED	DATE	JUNE 6, 1963	MUC	7440X															
2	DATE	PREPARED/REVISED	DATE	JUNE 6, 1963	MUC	7440X																			
3	INDEX	83																							
4	DATE	CP	TIME	AND	HAIR ACTION	HAIR TYPE 1	TOTAL	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION
5	DATE	CP	TIME	AND	HAIR ACTION	HAIR TYPE 1	TOTAL	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION	SCHED	UNION
6	JAN	42	651	41	1	126	14.00	4.00	4	437	142														
7	FEB	47	827	34	1	136	14.00	4.00	4	384	145														
8	MAR	53	1041	38	2	218	22.00	5.00	2	533	154														
9	APR	58	1004	53	2	208	23.00	5.00	5	722	191														
10	MAY	69	1525	36	2	181	20.00	6.00	5	815	138														
11	JUN	75	1325	39	2	127	30.00	7.00	4	615	219														
12	JUL	77	1626	44	1	188	31.00	9.00	6	875	176														
13	AUG	83	1593	54	1	127	35.00	9.00	2	1096	306														
14	SEP	93	1518	43	1	154	33.00	15.00	2	723	285														
15	OCT	155	3046	74	4	216	51.00	16.00	5	1297	514														
16	NOV	169	2633	69	2	225	44.00	14.00		1390	495														
17	DEC	188	2461																						
18	TOTAL																								
19	1ST QTR																								
20	2ND QTR																								
21	3RD QTR																								
22	4TH QTR																								
23	YEAR																								
24	THREE MONTH MOVING AVERAGE																								
25	THREE MONTH MOVING AVERAGE																								

FIGURE H-5. AFG-66 Radar Maintenance Summary

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
2	DATE	PREPARED/REVISED	FILENAME	DATE	JUNE 6, 1963	MIC 7400X																			
3	DISK #3																								
4	DATE	TIME	AVG	OP	FAIL	CRV/MAL	TOT TYPE 1	TOT TYPE 2	TOT TYPE 3	TOT TYPE 4	TOT TYPE 5	TOT TYPE 6	TOT TYPE 7	TOT TYPE 8	TOT TYPE 9	TOT TYPE 10	TOT TYPE 11	TOT TYPE 12	TOT TYPE 13	TOT TYPE 14	TOT TYPE 15	TOT TYPE 16	TOT TYPE 17	TOT TYPE 18	
5	JAN	201	2492	1	69	4	180	37.00	13.00	23	1054	670	40	73	111	47	57.28	38.01	24.82	26.92	14.96	109	0.174591382	2439	
6	FEB	143	2515	1	102	4	293	28.00	10.00	20	1815	989	38	54	75	73	22.66	34.66	25.15	5207	8.36	187	0.044335088	28954	
7	MAR	157	3233	1	101	3	331	29.00	10.00	12	2847	820	25	64	104	40	40.92	32.01	32.33	11847	9.96	217	0.024435088	30187	
8	APR	167	3407	1	114	11	342	29.00	10.00	12	2847	820	25	64	104	40	40.92	32.01	32.33	11847	9.96	217	0.024435088	30187	
9	MAY	176	3415	1	104	5	311	32.00	11.00	18	2798	1334	63	69	133	69	32.76	32.84	34.15	15262	10.98	202	0.030525389	33594	
10	JUN	188	3756	1	103	6	295	33.00	11.00	23	2458	828	28	69	97	97	35.68	36.82	37.56	19018	12.73	187	0.0258253461	40765	
11	JUL	196	4659	1	86	8	245	41.00	14.00	7	2051	544	24	38	62	62	75.15	54.17	46.59	23677	19.02	151	0.133075767	45424	
12	AUG	195	1055	1	106	66	438	32.00	10.00	62	2514	1563	74	124	198	198	5.33	9.95	10.55	24732	2.41	266	0.187677251	46479	
13	SEP	219	3449	1	90	13	248	32.00	10.00	39	3465	1567	48	43	77	77	44.79	36.32	34.49	28181	13.91	145	0.022323117	49928	
14	OCT	236	4912	1	127	10	402	29.00	9.00	36	2695	1341	62	87	136	136	36.12	38.68	49.12	33093	12.22	265	0.0276872964	54840	
15	NOV	226	5112	1	77	8	297	46.00	14.00	36	2695	1341	62	87	136	136	33.85	66.39	51.12	38205	17.21	212	0.0295383412	59952	
16	DEC	240	5071	1	93	7	322	51.00	15.00	6	2401	982	27	77	104	104	48.76	54.53	50.71	43276	15.75	222	0.0205087754	65023	
17	TOTAL																								
18	1ST QTR	167	8440	0	272	9	804	31.03	10.50	50	4716	2479	70	147											
19	2ND QTR	177	10578	1	320	22	948	33.06	11.16	53	7841	3102	131	1	202										
20	3RD QTR	203	9163	0	282	87	931	32.49	9.84	69	7910	3510	132	0	265										
21	4TH QTR	234	15095	0	297	143	3704	36.96	11.68	253	29028	12981	470	2	827										
22	YEAR																								
23	THREE MONTH MOVING AVERAGE																								

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6	DATE	TIME	AVG	OP	FAIL	CRV/MAL	-MAINT ACTION-				-HOURS-				-ACTION UNITS-				TOT REPR		-COND 6				TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6		TOT REPR		COND 6			

FIGURE H-6. APG-66 Radar Maintenance Summary

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1	1979168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	168	
2	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	PREPARED	REVISED	DATE	
3	DESK	812																								
4	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	
5	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	INV	TIME	ARO	DATE	
6	JAN																									
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22	3RD	QTR																								
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FIGURE H-7. APG-66 Radar Maintenance Summary



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FIGURE H-8. APG-66 Radar Maintenance Summary

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	19061715A/B	C/D	DD568	DATA	FILENAME	14-10																			
2	DATE PREPARED/REVISED				DATE	JUNE 6, 1983	MIC 74PXX																		
3	DISK 816																								
4																									
5	DATE	TIME	NO	OP	FAIL	CHN/VAL	TOT TYPE 1	TOTAL	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	
6	JAN	438	9308	1	343	13	855	74.00	31.00	13	7002	11387	494	5	280	779	11.95	25.64	9308	10.89	479	.0836914482	237763		
7	FEB	441	8643	7	404	23	916	73.00	32.00	25	7561	9527	425	4	174	603	14.37	21.44	8643	9.46	489	.0896063719	246416		
8	MAR	443	9035	7	430	26	1108	62.00	26.00	15	9795	12512	575	7	348	616	14.67	21.01	9035	8.15	452	.0881793027	255451		
9	APR	457	9810	2	453	17	1097	56.00	23.00	15	9283	12660	533	2	348	883	11.21	21.66	9810	8.94	627	.0900101937	265261		
10	MAY	457	9810	2	453	17	1200	46.00	18.00	15	9283	12798	750	10	299	1059	7.87	17.21	8330	45.46	689	.1271308523	273591		
11	JUN	393	9188	6	608	34	1292	37.00	15.00	12	9737	12374	558	10	296	854	10.67	12.51	9188	6.94	650	.0929473226	282779		
12	JUL	474	8586	3	604	39	1401	31.00	14.00	12	11360	13233	545	1	256	802	10.76	15.11	8587	6.24	699	.0937244361	291336		
13	AUG	463	8596	4	647	32	1378	29.00	14.00	23	11723	19085	590	1	381	963	8.94	13.29	8596	6.86	648	.1575637592	308532		
14	SEP	483	8587	4	580	23	1251	29.00	14.00	14	11094	22382	1024	8	321	1353	6.25	14.81	8587	6.46	648	.0767037616	319392		
15	OCT	493	10873	2	640	51	1337	30.00	15.00	32	10958	21938	502	1	322	834	13.04	16.99	10873	8.13	646	.0767037616	319392		
16	NOV	493	8387	8	577	59	1360	32.00	15.00	9	11606	21434	558	1	322	885	9.48	14.54	8387	6.17	724	.1055204483	327779		
17	DEC	495	9260	3	370	32	866	36.00	17.00	5	7870	13133	320	1	226	547	16.93	25.03	9260	10.69	464	.0590712743	337039		
18																									
19	ANG	TOTAL	TOTAL				TOTAL	ANG	ANG	TOT	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL									
20	1ST QTR	441	27006	15	1197	62	2879	22.56	9.38	53	24358	34426	1494	16	488										
21	2ND QTR	434	27328	11	1545	78	3589	7.61	6.11	66	28756	42352	1841	12	943										
22	3RD QTR	474	25740	11	1911	94	4030	13.47	6.38	69	34177	50700	2149	10	958										
23	4TH QTR	490	28520	13	1587	142	3563	17.97	8.00	46	38434	56505	1380	1	885										
24	YEAR	495	108594	50	6240	376	14061	17.40	7.72	234	117725	183983	6864	39	3274										
25	THREE MONTH MOVING AVERAGE																								

1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y											
1	1901750/B C/D DD568 DATA												FILENAME												15-11											
2	DATE PREPARED/REVISED												DATE												JUNE 6, 1983 MIC 74PXX											
3	DISK 816																																			
4																																				
5	DATE	TIME	NO	OP	FAIL	CHN/VAL	TOT TYPE 1	TOTAL	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON	SCHED	UNCON												
6	JAN	511	9314	3	669	83	1493	35.00	16.00	28	11628	17941	524	322	846	11.01	18.26	9314	8.33	741	.0908310071	346353														
7	FEB	462	9880	5	541	47	1186	39.00	18.00	19	10027	17126	412	261	673	14.68	19.74	9880	8.14	598	.0681174089	356233														
8	MAR	507	11271	2	571	42	1384	35.00	17.00	11	10034	21171	549	348	897	12.57	19.75	11271	7.53	771	.0795847751	367504														
9	APR	521	11354	6	575	75	1508	39.00	17.00	45	12818	20199	472	351	823	13.80	19.36	11354	8.22	858	.0724854677	378858														
10	MAY	495	10261	2	530	64	1249	41.00	17.00	35	9970	21139	479	1	309	789	13.01	22.35	10261	52080	655	.0768930903	388119													
11	JUN	533	11374	6	509	58	1221	46.00	19.00	32	10716	18928	423	1	256	680	16.73	22.35	11374	63454	654	.0597854756	400493													
12	JUL	541	11879	3	624	48	1316	43.00	19.00	5	11348	21329	570	305	875	13.58	19.04	11879	75333	644	.0736593889	412372														
13	AUG	496	10376	5	793	50	1518	36.00	18.00	23	12762	20055	776	447	1223	8.48	13.08	10376	85709	675	.1178681573	432748														
14	SEP	589	9744	5	491	30	1084	33.00	16.00	4	8505	18476	494	268	762	12.79	19.85	9744	95453	563	.0792019704	432492														
15	OCT	586	12242	3	659	60	1402	34.00	16.00	8	11925	27078	570	4	328	902	12.37	18.58	12242	107695	683	.0736807711	444734													
16	NOV	455	9075	8	504	46	1128	41.00	19.00	8	10216	14507	440	1	297	738	12.30	18.01	9075	116770	578	.0813223140	452889													
17	DEC	563	10323	4	492	42	1176	44.00	20.00	10	10515	19924	428	204	632	16.33	20.98		127093	642	.0612225126															
18																																				
19	ANG	TOTAL	TOTAL				TOTAL	ANG	ANG	TOT	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL																					
20	1ST QTR	493	30465	10	1781	172	4063	17.11	7.50	56	31690	56238	1485	0	931																					
21	2ND QTR	516	32989	14	1614	197	3978	20.44	8.29	112	33504	60266	1374	2	916																					
22	3RD QTR	542	31999	13	1908	128	3918	16.77	8.17	32	32615	59860	1840	0	1020																					
23	4TH QTR	535	31640	15	1655	148	3706	19.12	8.54	26	32856	51509	1438	5	829																					
24	YEAR	522	127093	52	6958	645	15665	18.27	8.11	228	130465	278773	6137	7	3696																					
25	THREE MONTH MOVING AVERAGE																																			

FIGURE H-9. APG-63 Radar Maintenance Summary

1		A		B		C		D		E		F		G		H		I		J		K		L		M		N		O		P		Q		R		S		T		U		V		W		X		Y		Z	
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
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1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23		24		25					
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**FIGURE H-10. APG-63 Radar Maintenance Summary**

FILE NAME FOURTEEN										DATE JUNE 6, 1983 MUC 74PDC										1900715 A/B D568										Dsk 11																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
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### FIGURE H-12. APG-63 Radar Maintenance Summary

A B C D E F G H I J K L M N O P Q R S T U V W X									
170715C/D 0556 DATA									
FILE NAME									
DATE PRESERVED/REVISED									
JUNE 6, 1983									
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### FIGURE H-14: APG-63 Radar Maintenance Summary

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### FIGURE H-18. F4E Radar Maintenance Summary

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### FIGURE H-19. F4E Radar Maintenance Summary

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FIGURE H-20. F4E Radar Maintenance Summary

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	APG-66 RECORDS														
2	DATE PREPARED														
3															
4															
5															
6	REC														
7															
8															
9	74000 FIRE CONTROL RADAR SET														
10	74000 SET OTHERWISE CLOD														
11	74000 ANTENNA RADAR														
12	74000 LOW POWER RF UNIT														
13	74000 TRANSMITTER RADAR														
14	74000 PROC DIGITAL SIG PROC GP 1														
15	74000 RADAR COMPUTER														
16	74000 RADAR CONTROL PANEL														
17	74000 RADAR BACK ASSEMBLY														
18	74000 COAX INET DR/SP LIN														
19	74000 CIRCULAR MAGNETIC														
20															
21	TOTAL														
22															
23	% of Overall Total														

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	APG-66 RECORDS														
2	DATE PREPARED														
3															
4															
5															
6	REC														
7															
8															
9	74000 FIRE CONTROL RADAR SET														
10	74000 SET OTHERWISE CLOD														
11	74000 ANTENNA RADAR														
12	74000 LOW POWER RF UNIT														
13	74000 TRANSMITTER RADAR														
14	74000 PROC DIGITAL SIG PROC GP 1														
15	74000 RADAR COMPUTER														
16	74000 RADAR CONTROL PANEL														
17	74000 RADAR BACK ASSEMBLY														
18	74000 COAX INET DR/SP LIN														
19	74000 CIRCULAR MAGNETIC														
20															
21	TOTAL														
22															
23	% of Overall Total														

FIGURE H-21. APG-66 Removal Data



A    B										C    D    E    F    G    H    I    J    K    L    M    N    O									
175C REMOVALS										MARCH 82-FEB 83									
DATE PREPARED										JUNE 7, 1983									
ON EQUIPMENT										OFF EQUIPMENT									